DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH

ATMOSPHERIC POLLUTION RESEARCH

TECHNICAL PAPER No. 1

ATMOSPHERIC POLLUTION IN LEICESTER

A SCIENTIFIC SURVEY

LONDON: HIS MAJESTY'S STATIONERY OFFICE
1945
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a loss of results from instrumental defects, while the work of analysing and abstracting the maximum amount of information from the observational data —testing each point to see if the errors of observation allow the conclusions to be trustworthy—is formidable indeed.

Two members of the Committee, Dr. J. S. Owens and Dr. F. J. W. Whipple, have died since the work at Leicester was begun. Dr. Owens had long been associated with the investigation of atmospheric pollution and latterly had been Superintendent of Observations. Both he and Dr. Whipple gave much valuable help in organizing the work described in this report.

G. M. B. DOBSON,
Chairman,
Atmospheric Pollution Research Committee.

April, 1944.

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Notes on the Arrangement of the Report

The section numbers are quoted wherever a cross reference is made in the text.

Tables and diagrams are not numbered consecutively, but are given the number of the section to which they belong.

References to other publications are collected at the end of the report.

TABLE OF METRIC AND BRITISH MEASUREMENTS USED IN THIS REPORT

Length

1 Ångstrom unit $=10^{-10}$ metre $=0{\cdot}0001$ micron
1 micron (μ) $=10^{-5}$ metre $=0{\cdot}0001$ cm.

1 cm. = 10 mm. = 0·394 inch	1 inch = 2·540 cm.
1 metre (m.) = 1·094 yard = 3·281 feet	1 yard = 0·914 m.
1 kilometre (km.) = 0·621 mile	1 mile = 1·609 km.

Area

1 sq. cm. = 0·155 sq. inch	1 sq. inch = 6.452 sq. cm.
1 sq. m. = 1·196 sq. yard	1 sq. yard = 0·836 sq. m.
1 sq. km. = 0·386 sq. mile	1 sq. mile = 640 acres = 2·590 sq. km.

Volume

1 c.c. (ml.) = 1000 mm.^{3} = 0·061 cu. in.	1 cu. in. = 16·39 c.c.
1 litre (l.) = 1000 ml. = 0·035 cu. ft.	1 cu. ft. = 6·23 gallons = 28·32 litres
1 m.^{3} = 1000 l. = 1·308 cu. yd.	1 cu. yd. = 0·765m.^{3}

Mass

1 gram (g.) = 1000 milligrams (mg.) = 10^6 micro-grams (μg.) = 15·43 grains	1 grain = 0·065 gram
1 kilogram (kg.) = 2·205 pounds (lb.)	1 lb. = 0·454 kg.
1 tonne = 1000 kg. = 0·984 ton	1 ton = 1·016 tonne

Temperature

Ice point: 0° Centrigrade = 273° Absolute = 32° Fahrenheit

Steam point: 100°C. = 373°A. = 212°F.

Temperature difference: 1°C. = 1·8°F. 1°F. = 0·556°C.

Temperature gradient: 1°C. /m. = 0·549°F. /ft. 1°F. /ft. = 1·823°C. /m.

Velocity

1 metre/sec. = 3·28 ft. /sec. = 2·237 miles/hr.
1 mile/hr. = 1·467 ft. /sec. = 0·447 metre/sec.

Acceleration due to gravity: g = 981 cm. /sec.^{2} = 32·2 ft. /sec.^{2}

Deposit

1 gram/m.^{2} = 1 tonne/km.^{2} = 2·55 tons/sq. mile = 9 lb. /acre
1 ton/sq. mile = 0·392 tonne/km.^{2}
1 mg. /100 cm.^{2} = 1·29 grain/sq. yd.
1 grain/sq. yd. = 0·776 mg. /100 cm.^{2}

Suspended Matter

1 mg. /m.^{3} = 0·0118 grain/cu. yd.
1 grain/cu. yd. = 84·8 mg. /m.^{3}

Concentration of Sulphur Dioxide in Air (approximate)

1 volume of SO_2/million volumes of air = 0·00062 grain Sulphur/cu.ft. = 0·00143 mg. Sulphur/litre

1 mg. S/litre = 0·436 grain S/cu. ft. = 700 vols. SO_2/million

1 grain S/cu. ft. = 2·3 mg. S/litre = 1610 vols. SO_2/million

ATMOSPHERIC POLLUTION IN LEICESTER

A SCIENTIFIC SURVEY

1·0 INTRODUCTION

1·1 Organization

During the three years 1937-9, three officers of the Department of Scientific and Industrial Research were engaged full-time in making systematic observations of atmospheric pollution in the City of Leicester with the full co-operation of the City Authorities. The object was not only to obtain information about the distribution and dispersal of atmospheric pollution which would be peculiar to Leicester, but to secure new basic knowledge about atmospheric pollution which would be of more general application. The present report is an account of the results of this work and of the conclusions, whether of special or general application, which may be drawn from them.

The Leicester Survey was planned and supervised by the Atmospheric Pollution Research Committee of the Department of Scientific and Industrial Research, but the cost of the Survey was partly met out of a fund accumulated from subscriptions of a number of municipal, industrial, and other bodies which associated themselves with the Department in a study of atmospheric pollution.

The Atmospheric Pollution Research Committee wish to acknowledge their indebtedness to the Leicester City Council, and particularly to the officers of the City of Leicester Public Health Department, for their very substantial help in organizing and carrying out the survey. In addition to providing office and laboratory accommodation, the Leicester authorities provided accommodation for 12 of the 17 observing stations, and maintained observations at one of them. Most important of all was the City Health Committee's decision to set up and maintain a fully equipped climatological station at their City General Hospital. The Atmospheric Pollution Research Committee are also deeply grateful to the Visiting Committee of the City Mental Hospital, Leicester, the Principal of University College, Leicester, and the President of the Leicester and County Saturday Hospital Society for providing accommodation for observing stations and assistance in taking observations; also to Mr. J. E. White, proprietor of the Glen Gorse Golf Club, and to the Council of Scraptoft Golf Club, for providing accommodation for observing stations. Their thanks are also due to Mr. E. W. Jackson and Messrs. Pattinson and Stead, of Middlesbrough, for the gift of an apparatus for taking hourly samples of sulphur dioxide, and for permission to publish a description of the apparatus.

1·2 Purpose

The removal or, better still, the prevention of atmospheric pollution is part of the general problem of living healthily and happily in communities, because the quality of the air we breathe is just as important as the purity of our food and water. To solve this problem, the nature and behaviour of atmospheric pollution must first be understood. In spite of the systematic observations and special researches made in recent years, little was known about the distribution of atmospheric pollution in towns, or about its persistence or dispersal, and

there was even doubt as to its place of origin. The survey of pollution in Leicester was therefore undertaken to increase our knowledge of these general questions. The need to rebuild bombed areas has now brought an opportunity to apply this knowledge much sooner, and on a much bigger scale, than had been expected.

It is well that the Leicester Survey was begun five years before this need arose, because much time was required both to make the necessary measurements and to extract the useful information which they held. The architects and engineers who have to prepare plans of residential and industrial districts will want to know, in simple terms, the answers to a number of questions which, hitherto, have not been answered satisfactorily. How much pollution is there in a town, and how is it distributed? Where and when is it produced? How much of it is produced by domestic buildings and how much by industrial undertakings? How far does it spread? By how much does it vary from day to day, between day and night, Sunday and weekday, summer and winter? Why does it so vary? How does it affect visibility and daylight? What are the best ways to measure it, and how should the measurements be interpreted? How is it removed? Can it be prevented?

The survey of pollution in Leicester was therefore devised:

(1) to measure and investigate the distribution of atmospheric pollution in the neighbourhood of an industrial town;
(2) to determine the principal agents causing atmospheric pollution;
(3) to measure how atmospheric pollution varies, e.g. with the habits of the population and with meteorological conditions;
(4) to find out how pollution escapes from the atmosphere of a town.

1·3 Method

Regular observations, made at a number of sites in or near Leicester over a period of three years, included the measurement and analysis of suspended and deposited impurity. In addition, measurements were made of the total amount of ultra-violet daylight, and for this purpose a new apparatus was devised by Dr. A. R. Meetham. The various instruments used are described in Chapter 2 of this report, and their locations during the experiments are summarized in Table 3·3. Regular meteorological observations were included in the programme, and the total number of readings of all kinds amounted to about 200,000.

This large number of readings was essential because neither meteorological conditions nor the amounts of atmospheric pollution emitted were under control. To interpret the data effectively, statistical methods were used, and a brief summary of the statistical technique is given in Appendix 6·1.

1·4 Results

It has thus been possible to estimate both the mean distribution of pollution in and around Leicester and the variations in distribution caused by wind or otherwise. The daily, weekly, and yearly cycles of atmospheric pollution have been examined and compared, and also a particular study has been made of the very large day-to-day variation of suspended impurity. In contradiction to the general impression that this day-to-day variation is mainly due to variations in wind velocity, the conclusions point to turbulence as the chief cause of the variability.

The apparatus mentioned in Section 1·3 was used to measure the distribution of ultra-violet daylight within a town, and to estimate the reduction of daylight caused by smoke and by clouds.

In Chapter 5 general conclusions of the work are reviewed, and practical suggestions are made on smoke abatement, sulphur control, and town planning; details are given of convenient ways to measure the effects of reforms which may be undertaken. There remain many gaps in our knowledge of the causes, distribution, and removal of atmospheric pollution. An attempt is made to summarize these deficiencies, and suggestions for further research are advanced.

2·0 APPARATUS

2·1 Introduction

Most of the apparatus used in the Leicester Survey was originally designed to measure pollution where it is abundant, i.e., near the centres of large towns. It was intended to give information about the production and effects of pollution in towns—whether it was decreasing or increasing with time, whether special civic action was having an appreciable effect, and so on. In the Leicester Survey, however, very low as well as high concentrations of pollution were measured, but the same apparatus was used throughout: firstly, because it was the best then available for the purpose, and because the results of this enquiry were required before better apparatus could be designed; secondly, to find out what interpretations to place on results obtained by numerous other users of the same apparatus, particularly on those results which are issued annually by the Department of Scientific and Industrial Research[1]*; and thirdly, to find whether the apparatus could be improved.

Each item of apparatus will now be considered in turn. A description of each instrument will be followed by a consideration of the physical meaning of the observations it takes; finally there will be a discussion of its defects. It is most important to understand each instrument in this way, before attempting to draw conclusions from the results it gives.

2·2 The Deposit Gauge

This was the earliest instrument to be standardized for use by Local Authorities in this country. Its modern form is described in the 14th and 18th Annual Reports of the Investigation of Atmospheric Pollution.[2] Its purpose is to collect, by means of a large funnel and bottle, the entire material deposited in one month on the surface presented by the funnel. The instrument should be exposed on a site where the deposited matter will be typical of the surrounding neighbourhood. The deposit may include:—

(i) rain, dew, melted snow and frost, and other forms of water;
(ii) soluble impurities dissolved in rain, either during its descent or while in the form of a cloud;
(iii) soluble impurities deposited under their own weight and by chance contact with the inside of the funnel, and afterwards dissolved by rain water and washed into the bottle;
(iv) insoluble matter deposited under its own weight and by chance contact with the inside of the funnel, some of which may stick permanently to the funnel, while some may be washed into the bottle by rain; some may even be blown out of the funnel by the wind.
(v) insoluble matter washed out of the air by rain.

Evidently these items fall into two classes, which may conveniently be termed dry deposits and pluvial deposits. Each month's deposit, including that sticking to the inside of the funnel, is analysed into the following components:—

(i) Water.
(ii) Undissolved matter.
  (a) Total.
  (b) Soluble in carbon bisulphide ("tar").

* These numbers refer to the References on page 156.

(c) Other combustible matter insoluble in carbon bisulphide.
(d) Ash.

Note that the sum of (b), (c) and (d) is equal to (a).

(iii) Dissolved impurities.

(a) Total.
(b) Sulphur in the form of sulphites and sulphates
(c) Chlorine.
(d) Ammonia.
(e) Lime.
(f) Free acid.

The *p*H of the water, with its dissolved impurities, is also measured. Note that the sum of (b), (c), (d), (e) and (f) is *not* equal to (a).

It is convenient to call item (ii) (b) by the name tar, although it may contain constituents such as animal and mineral oils not produced from the distillation of coal. There is no simple name for item (ii) (c), although (ii) (b) and (ii) (c) together consist mainly of soot and a varying proportion of coke particles. Estimation of ammonia and free acid has now been discontinued. Both quantities are affected by bacterial action, which may be considerable during the month for which the instrument is exposed.

2·21 *Limitations of the Deposit Gauge*

2·211 *Casual errors*. When an attempt is made to discuss the meaning of a set of results from one or more deposit gauges, serious difficulties are encountered. In the first place the sampling errors are considerable. Two gauges exposed 5 yards apart at Kew Observatory yielded the following estimates of standard deviations of one month's observations, from observations extending from April, 1934, to March, 1938:—

1.	2. Std. Devn. of 1 obsn.	3. Std. Devn. % of mean
Volume of water	3 mm. of rainfall	6%
Total undissolved matter	0·32 tonne per km.^{2}	16%
Tar (soluble in CS_2)	0·02 ,, ,,	19%
Other combustible matter	0·20 ,, ,,	24%
Ash	0·17 ,, ,,	15%
Total dissolved impurity	0·54 ,, ,,	24%
Sulphur as SO_4''	0·20 ,, ,,	27%
Chlorine as Cl'	0·03 ,, ,,	13%
Ammonia as NH_4^+	0·03 ,, ,,	85%

(Lime and free acid are not on record)

Why these standard deviations are so high is not fully understood. Either the methods of analysis are being overtaxed, or particulate matter is heterogeneously dispersed even in an open situation such as Kew Observatory. Yet neither of these explanations seems entirely acceptable. The lowest standard deviation, apart from rainfall, is that of chlorine, whose dispersion is known to be more nearly homogeneous because the residues of evaporating sea-spray form a major source of atmospheric chlorine. The pollution at places other than Kew is known to be different in amount and in constitution, and the casual errors will be different also. Neither will casual errors be necessarily proportional to the quantity of pollution, because the accidental inclusion of insects, bird droppings, and other natural materials, will contribute to the casual errors of at least some of the constituents of deposited matter. Hence it

is not right to apply either the second or third column of the preceding table to deposit gauges at places other than Kew, though where accuracy is not needed the table may be used as a very rough guide. It shows that the rarest constituents—namely, tar, chlorine, and ammonia—should be expressed to the second decimal place, i.e., to 0·01 tonne per km². All other constituents should be expressed to the first decimal place. No useful meaning can be attached to figures beyond these limits.

2·212 *Further limitations.* The deposit gauge is rather like a thermometer hanging from a tree in a garden. The owner may read the thermometer accurately, but may find he cannot state to what this temperature refers. It refers to the mercury in the bulb of the thermometer, and that alone. It is not the air, the tree, the garden, the sunshine, or the radiation from the earth or sky whose temperature is measured, but some compound of all these things.

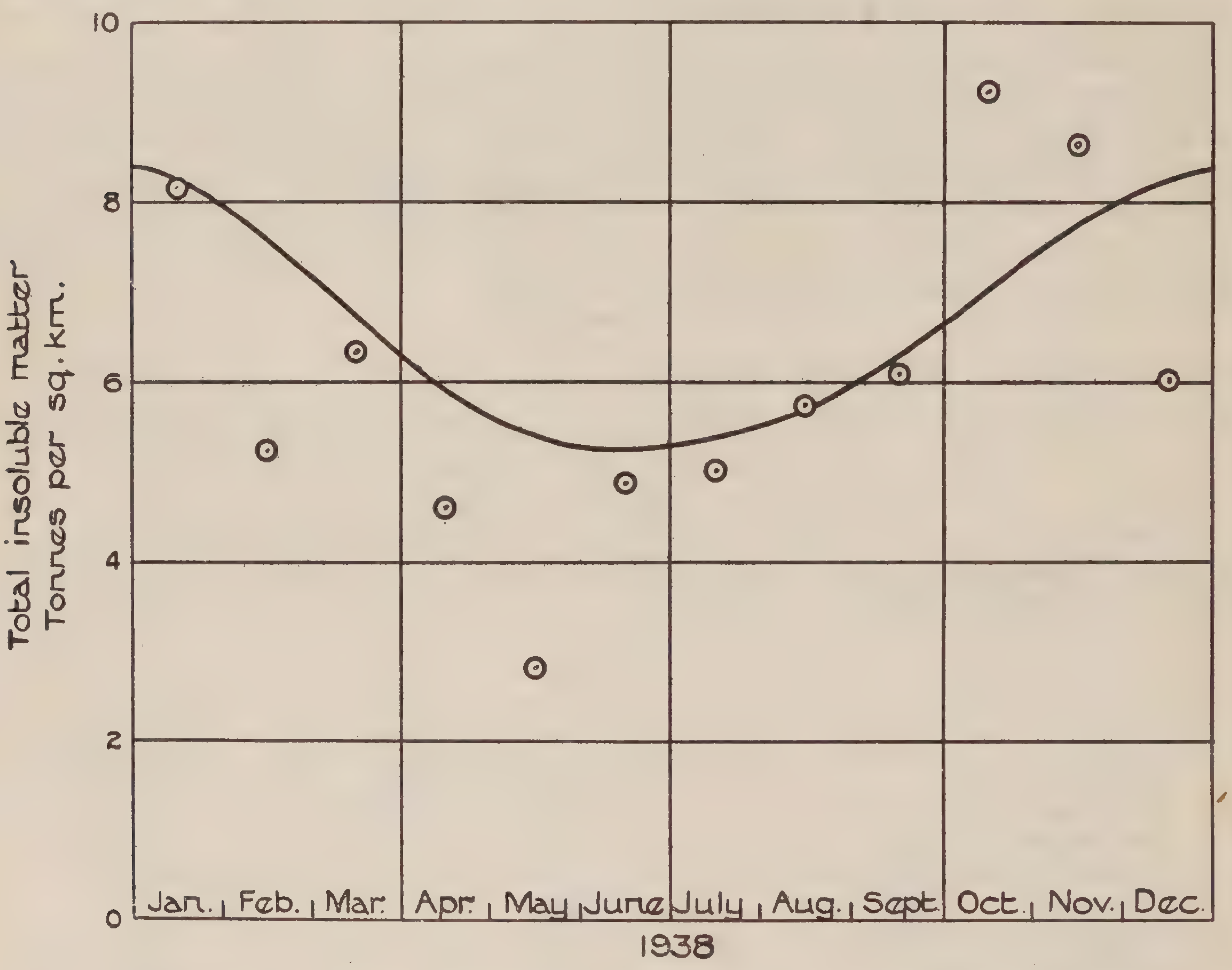


FIG. 2·212 MONTHLY TOTAL INSOLUBLE DEPOSIT AT LEICESTER TOWN HALL (1938).
Note: The smooth curve is from six years' observations ended March 1939.

Nevertheless, the thermometer reading may help him in deciding whether to plant out seedlings or whether to have tea served out of doors.

Similarly the deposit gauge measures no more than the rate of deposition of pollution in a bowl of 12 inches diameter. After considerable calculation and research, it is now known that the difference between two consecutive monthly deposits is associated with

rainfall,
wind direction,
turbulence,
trends—steady increases or decreases, } in emission
seasonal variation, } by chimneys.
irregular variations,
and possibly other factors.

The difference between two simultaneous deposits at two different places, on the other hand, is associated with the very elusive problem, "Which particular chimneys affect any given deposit gauge?" (Section 2·213). It is inconvenient that deposits are influenced by so many factors, but individual items on the above list may help to provide useful information. The effect of wind direction, for instance, may be valuable evidence about the direction from which a particular deposit originates. Also, like the thermometer above, a deposit gauge has its general uses. It may be a help in deciding the best site for a house or a cricket ground; or whether to instal a drying machine in a laundry.

The external relations of deposits, however, are inevitably obscured by this multiplicity of influences. For example, the annual variation of deposited matter may be influenced by annual variation of emission by domestic and industrial chimneys, annual variation of prevailing wind, rainfall and turbulence. The annual variation of deposited matter is also obscured by month-to-month variations of the same factors, of which rainfall and wind direction are probably the most important. Fig. 2·212 illustrates this last difficulty. One year's observations of monthly total insoluble matter deposited at Leicester Town Hall are plotted as twelve points. The smooth curve is taken from the mean of six years' observations, and represents an estimate of the periodic element which is supposed to have influenced the values of the twelve points. The points are in very poor agreement with the smooth curve, and this must be attributed to the influence of the other variable factors mentioned. Such difficulties as these have exact counterparts in meteorology and climatology; and it has long been realized that atmospheric pollution is largely a question of meteorology. Relevant meteorological data are tabulated in Appendix 6·4 of this report.

The standard deviation of single monthly observations of total insoluble matter deposited in winter at Leicester Town Hall is 27%, and Fig. 2·212 is consistent with this estimate. This could be reduced to about 22% if the casual errors of Section 2·211 could be eliminated. Or, by grouping five or six estimates together, the standard deviation would be reduced to about 12%. (This is the practice in Annual Reports of the Investigation of Atmospheric Pollution.) Or, if (a) extensive knowledge of the effects of rain and wind on deposits and (b) the meteorological records of rain and wind were available, an estimate of the mean winter value could be made from one month's observation, with a standard deviation of less than 13%. (This estimate is derived from Sections 4·61 and 4·64.)

Before discussions of deposits can go very far, it is therefore necessary to have considerable collateral evidence in the form of meteorological observations. Those who are concerned with deposit gauges know this only too well. The purpose here has been to emphasize this point and explain its causes. In Section 4·6 an attempt is made to discuss deposits at Leicester while making full use of collateral meteorological observations.

2·213 *Collecting range of the deposit gauge*. Comparison of deposits collected in different localities raises the question:—Within what region did each deposit originate? This question has not yet been answered satisfactorily. There can indeed be no definite answer, because (a) the region varies very much with wind direction (Section 4·61), (b) when it is raining a very much enlarged region influences the deposit gauge (Section 4·64).

It is obvious that results with deposit gauges cannot be adequately discussed without either knowing, or assuming, the instrument's effective collecting range. The tendency is to assume tacitly that in six months or more a deposit gauge receives a fairly uniform sample from all industrial chimneys within about ½ mile, provided that no important chimney is within 100 yards.

2·214 *The region represented by a deposit gauge* is quite another matter, although it is very liable to be confused with the region influencing the results.

A deposit gauge at a well chosen site should be representative of the average deposits experienced at any similar sites within a considerable distance. In the Annual Reports of the Investigation of Atmospheric Pollution deposit gauge results are expressed in tons per square mile, and it could be maintained that they really are the approximate weight, in tons, of the matter deposited on a square mile of horizontal area surrounding the deposit gauge. For this reason, gauges are placed if possible in the centre of large uniform districts, and great care is exercised in choosing sites. But until a series of observations has been made to determine the region represented by a deposit gauge in various typical sites, this question cannot be satisfactorily settled. The most ambitious attempt so far made in this country is at Glasgow, where 14 gauges have been in simultaneous use.

2·3 The Smoke Filter

The smoke* filter provides a very simple way of taking daily samples of the solid matter suspended in the air. With the aid of a filter pump, or small electrically driven pump, air from outside a building is drawn through a filter paper, at the rate of about 50 cu. ft. per day, the volume being measured with a gas meter. Each period of sampling lasts for 24 hours. The solid particles from the air are collected on the filter paper, and form a uniform circular stain one or two inches in diameter. The weight of pollution in a day's stain is estimated either

(1) visually, by comparing with Owens' standard scale of shades for the automatic filter (q.v., Section 2·4); or
(2) photometrically, by measuring the intensity of transmitted or reflected light with a standardized photo-electric cell and galvanometer.

Both the visual and the photometric method have been standardized by direct weighing, so that the weight of smoke corresponding with a given shade reading or a given galvanometer reading is known. Results are expressed as milligrams per cubic metre.

The smoke filter apparatus can conveniently be combined with the volumetric sulphur apparatus, described in Section 2·5.

2·31 *Conversion of Photometric Readings to Weights*

All routine smoke samples in Leicester were estimated photometrically as follows:—

A circular beam of red light, 0·8 in. in diameter and of a standard intensity, was passed through a clean filter paper into a photoelectric cell of the rectifier type, and the resulting photoelectric current was measured with a galvanometer. The filter paper was then exposed in the smoke filter apparatus, and the smaller photoelectric current produced by the standard red light on passing through the paper *plus* the smoke stain was measured. The difference between the two galvanometer readings constituted the photometric reading of the smoke stain.

Steps were taken to guard against unevenness of transmission through different parts of a filter paper, and to ensure that the photoelectric cell did not vary and that the standard intensity was always reproducible.

If smoke were always similar in composition there should correspond to each photometric reading a definite mass of material in a 1 in. circular smoke stain. The correspondence is not perfect in practice; the standard deviation of a single

* The word "smoke" will be used throughout this report for the black suspended impurity collected and indirectly weighed by air filters. In Section 2·321 it is shown that the principal constituent of suspended matter is soot, so that "smoke" describes it better than "dust." Smoke in this sense is often to be seen as a uniform haze or pall, reducing the visibility of objects across a town.

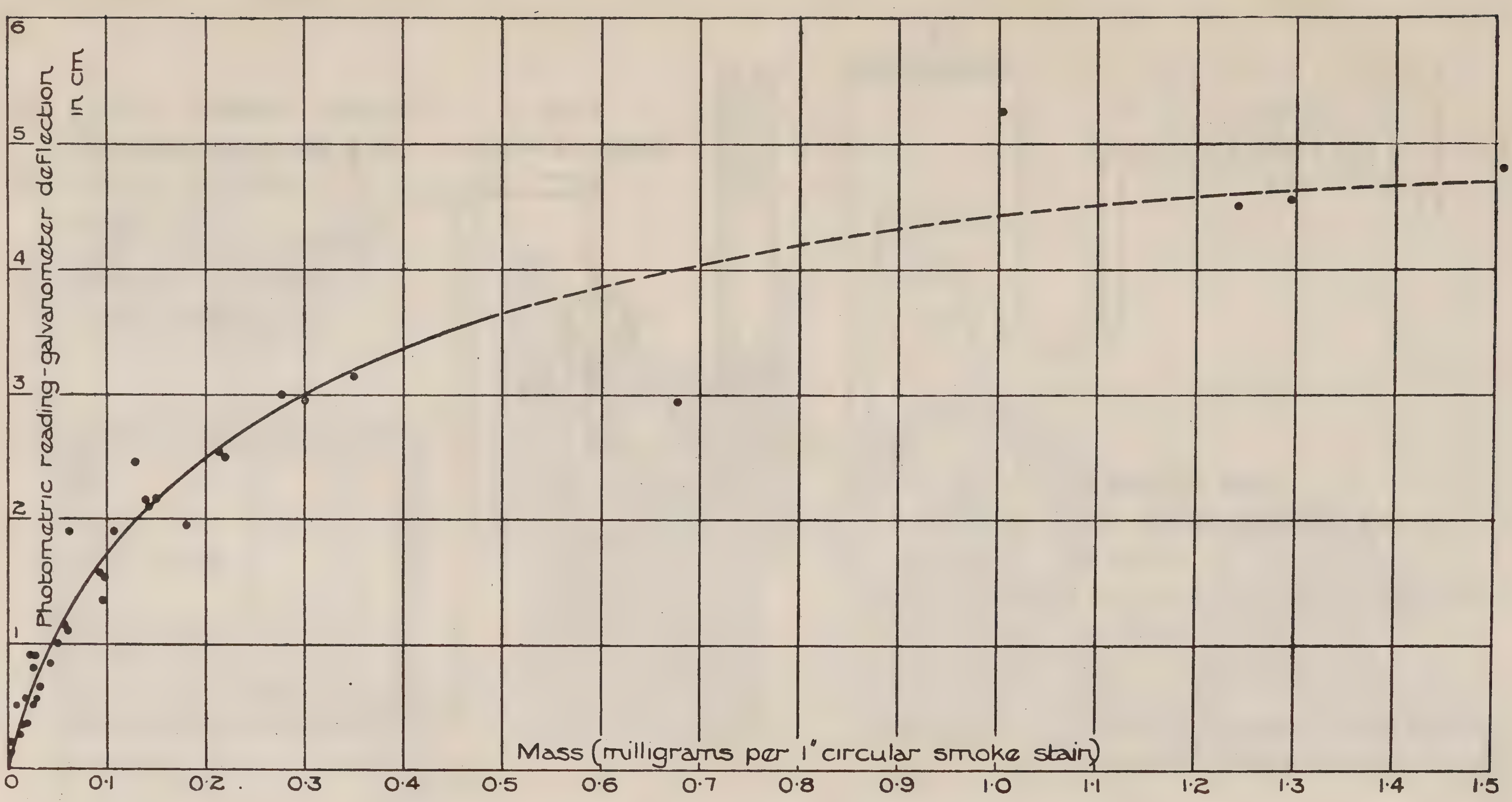
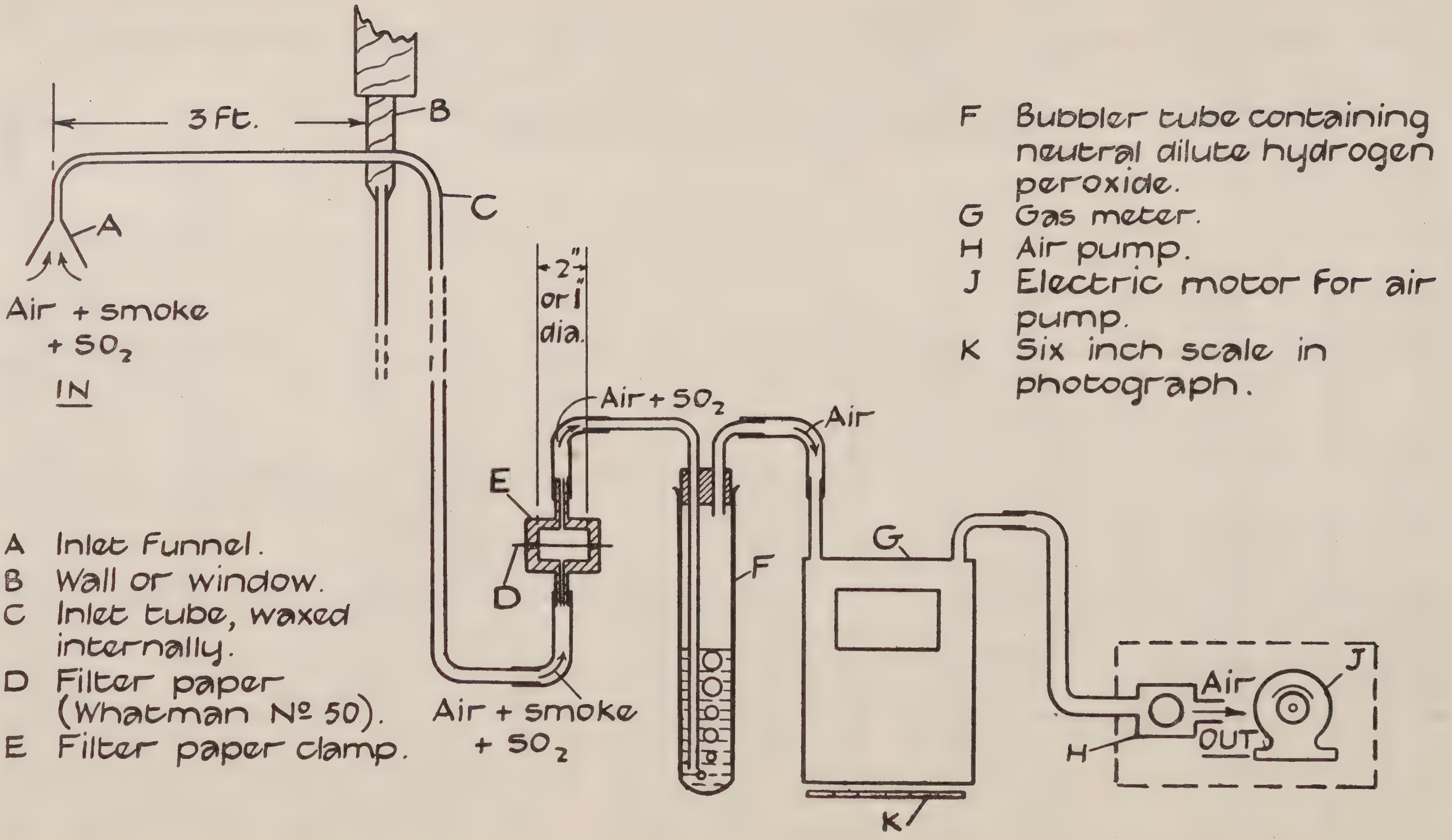
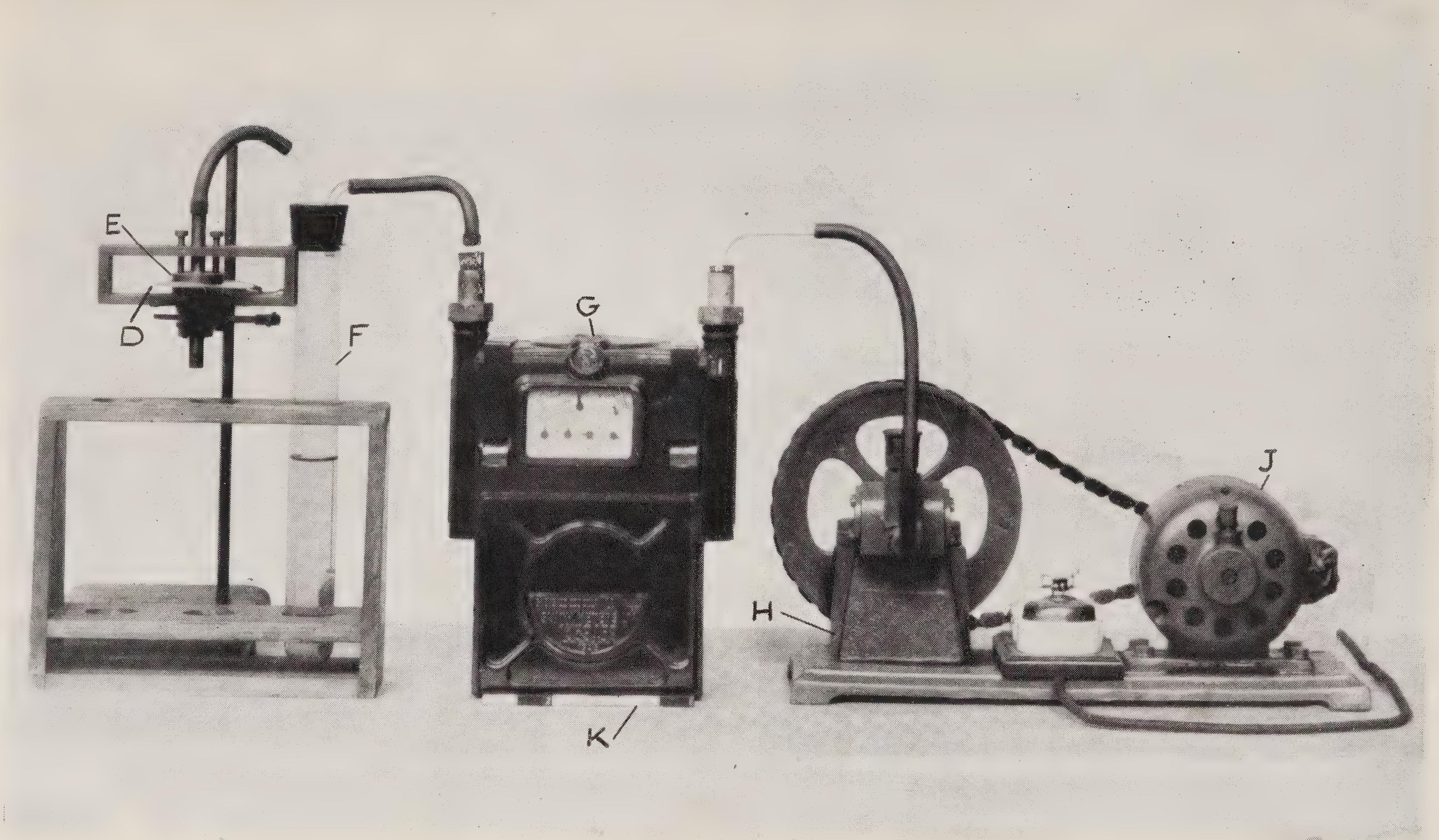


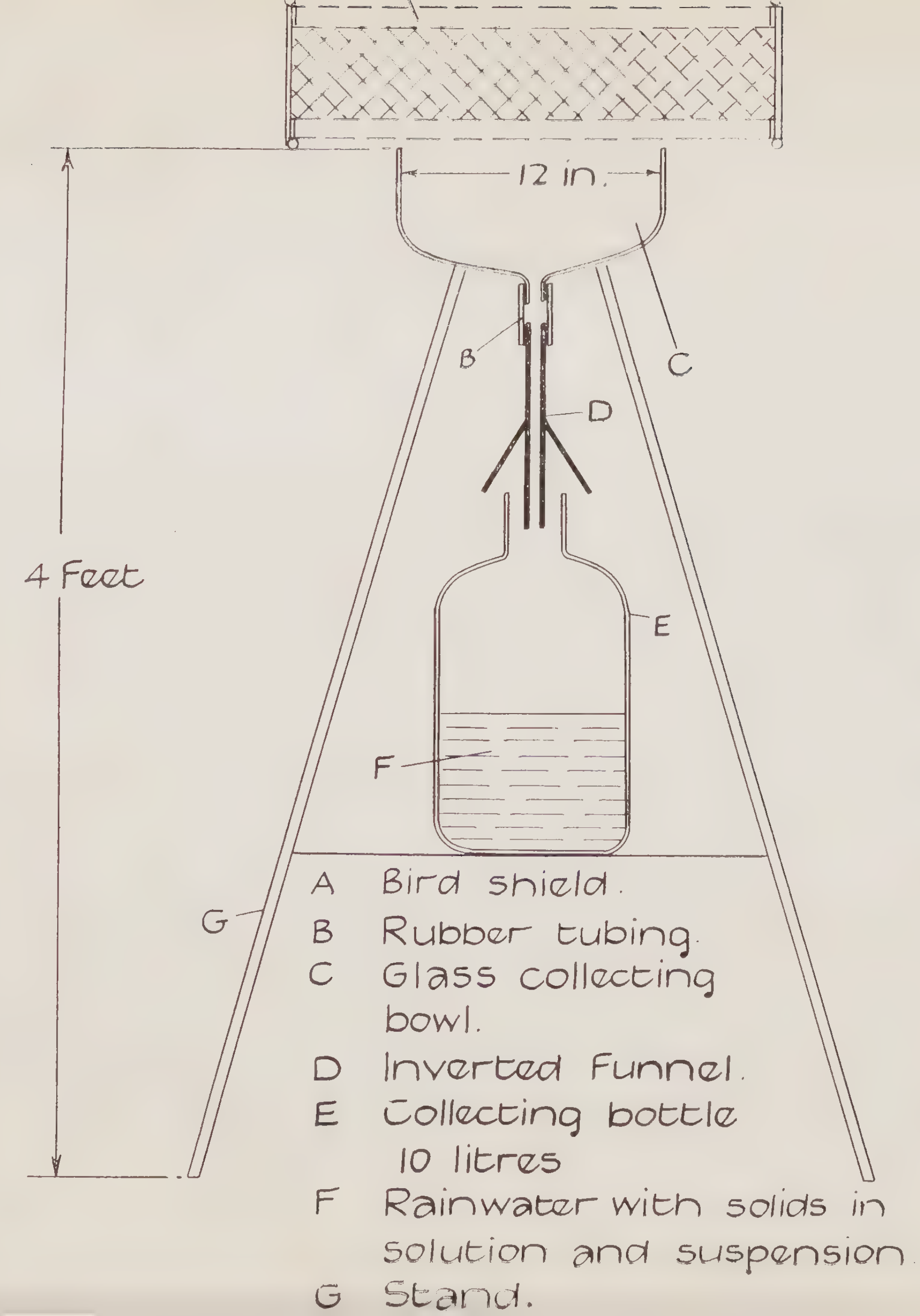
FIG. 2·31 CONVERSION OF PHOTOMETRIC SMOKE READINGS TO MASS.

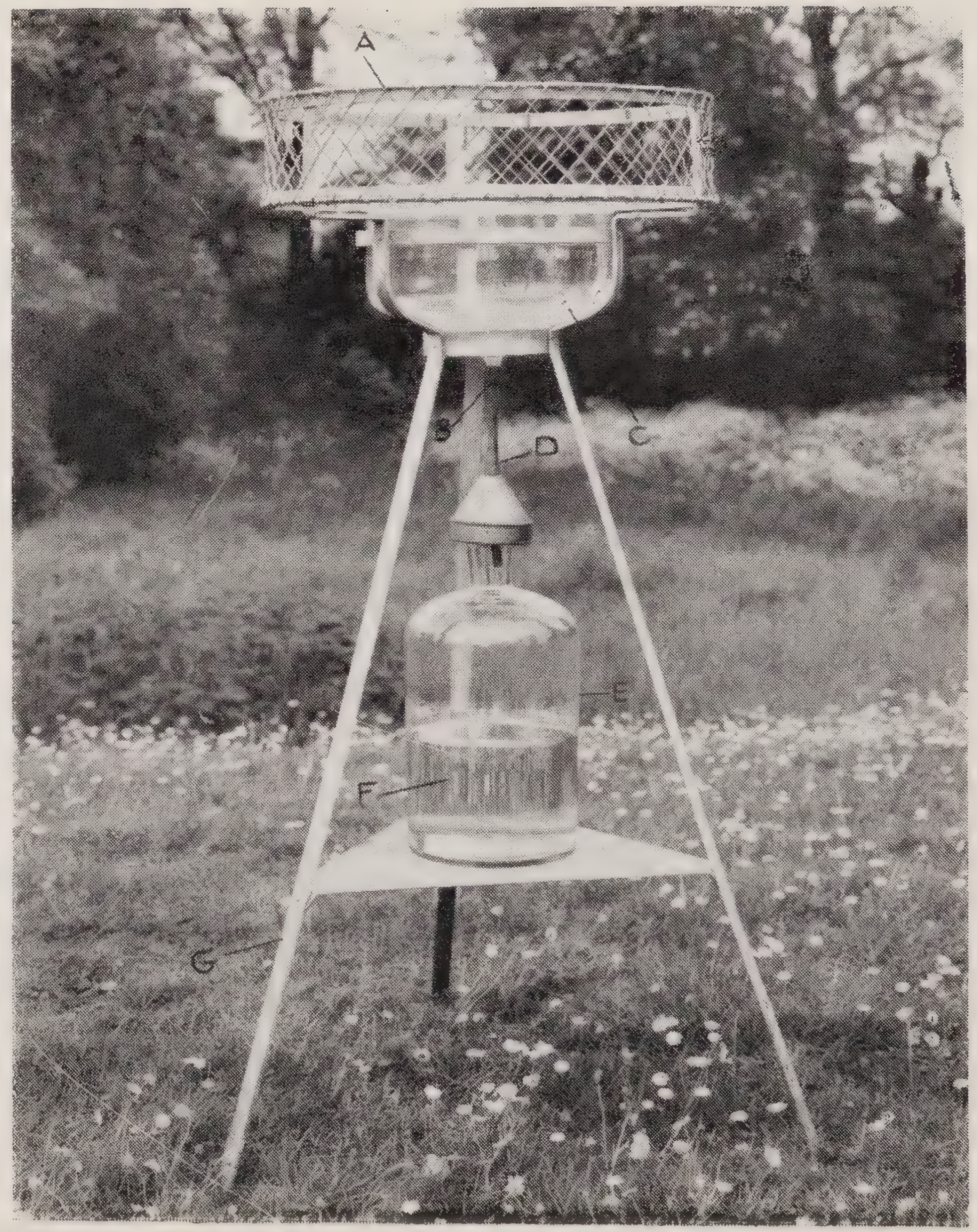
For a special photometer and Whatman No. 50 filter paper; giving the mass of material in a circular smoke stain of diameter 1 inch corresponding to any given photometric reading.


3 Ft.
B
C
A
Air + smoke + SO_2
IN
2" or 1" dia.
E
D
Air + SO_2
Air
Air + smoke + SO_2
F
G
K
H
J
Air
OUT
A Inlet Funnel.
B Wall or window.
C Inlet tube, waxed internally.
D Filter paper (Whatman № 50).
E Filter paper clamp.
F Bubbler tube containing neutral dilute hydrogen peroxide.
G Gas meter.
H Air pump.
J Electric motor for air pump.
K Six inch scale in photograph.



Volumetric Sulphur Dioxide Apparatus and Smoke Filter.
(For details, see diagram above.)


12 in.
4 Feet
A
B
C
D
E
F
G
A Bird shield.
B Rubber tubing.
C Glass collecting bowl.
D Inverted Funnel.
E Collecting bottle 10 litres
F Rainwater with solids in solution and suspension.
G Stand.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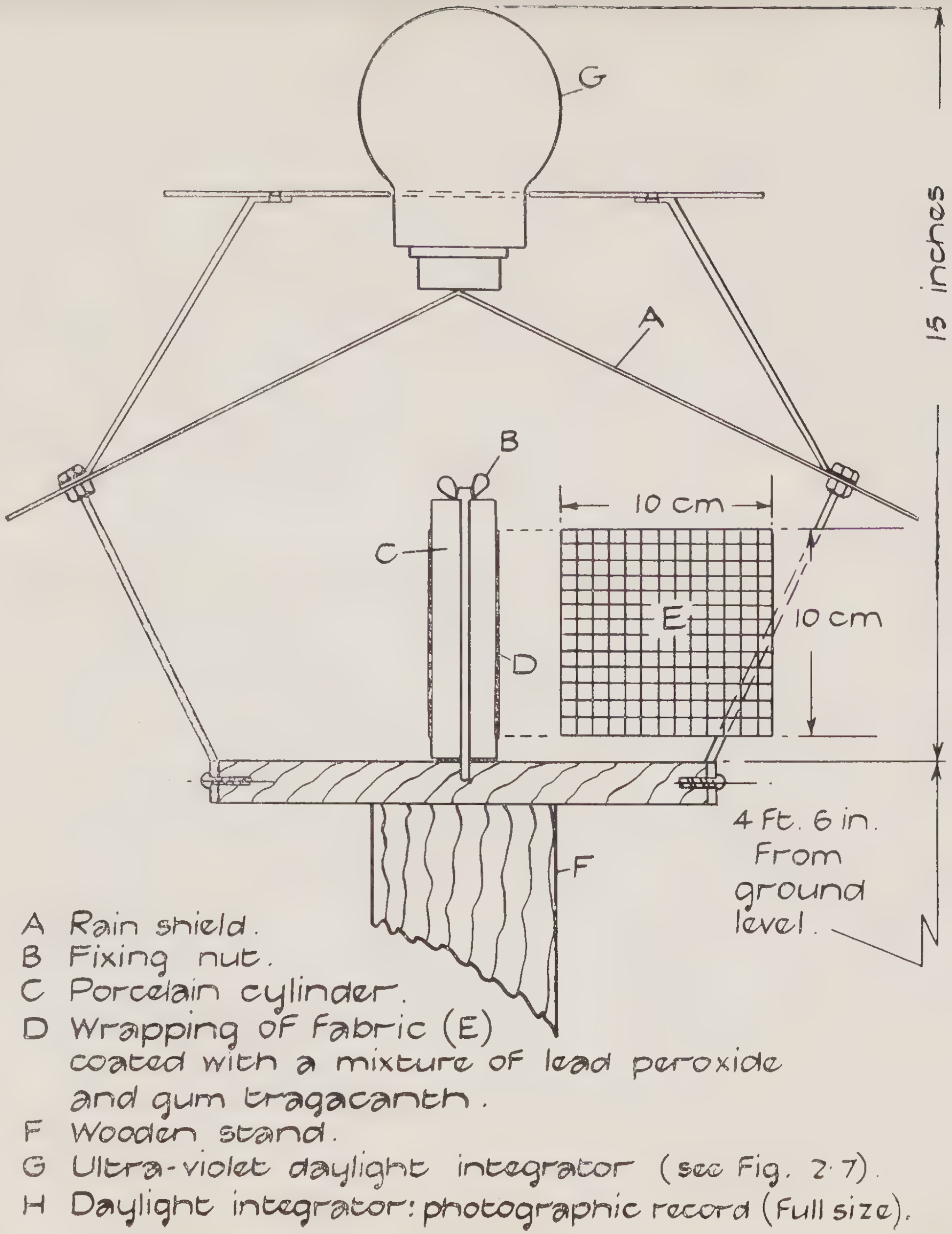
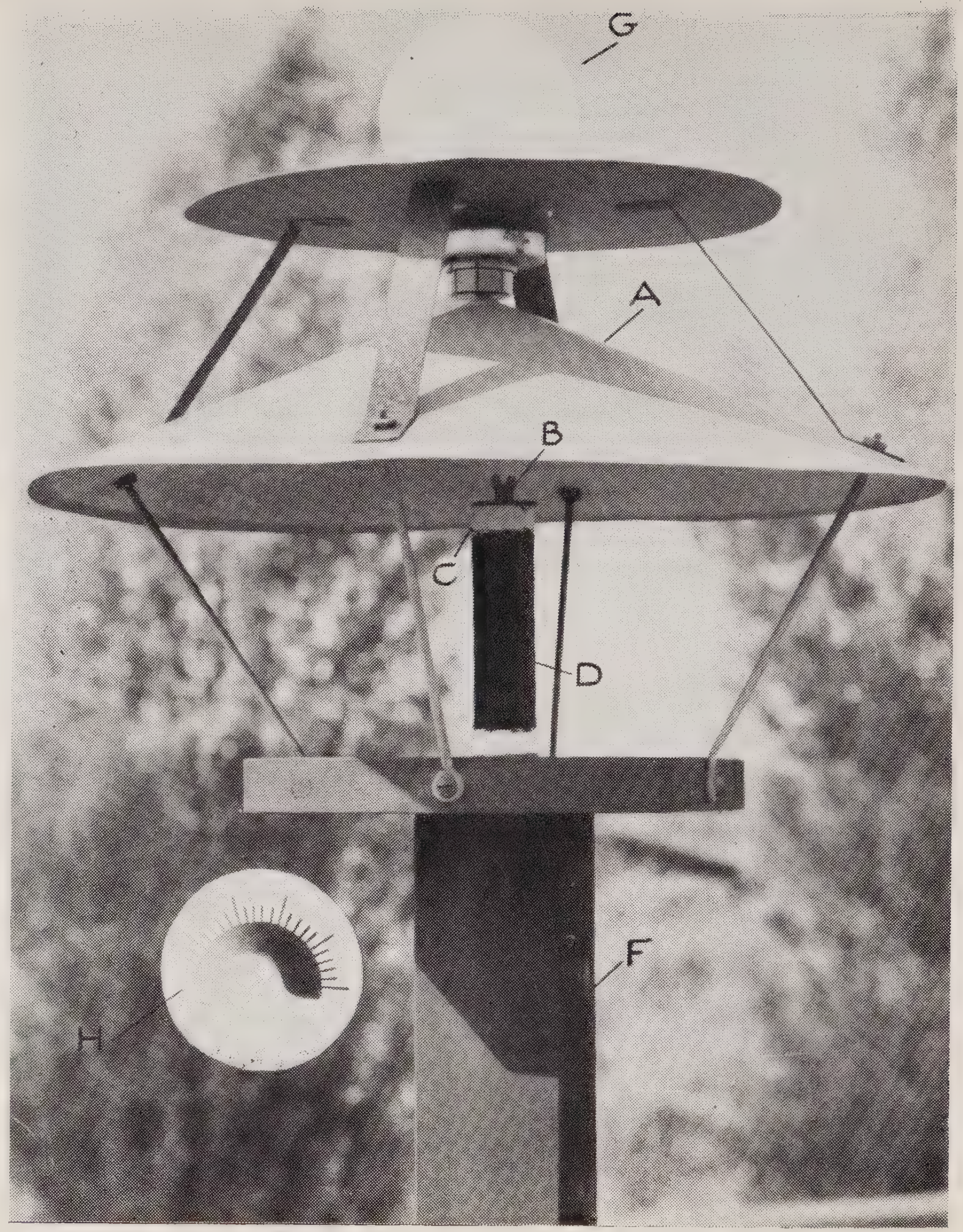
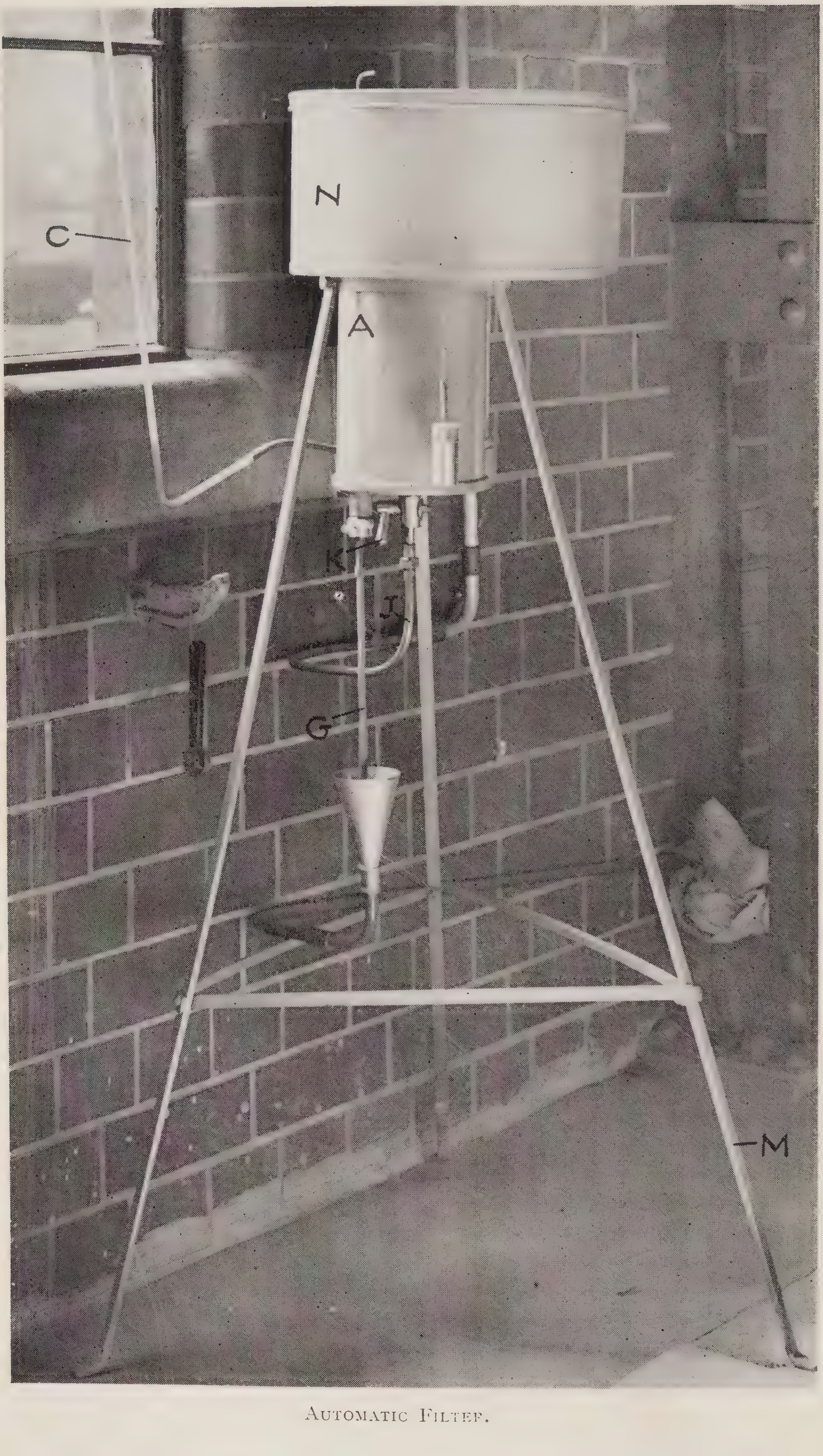
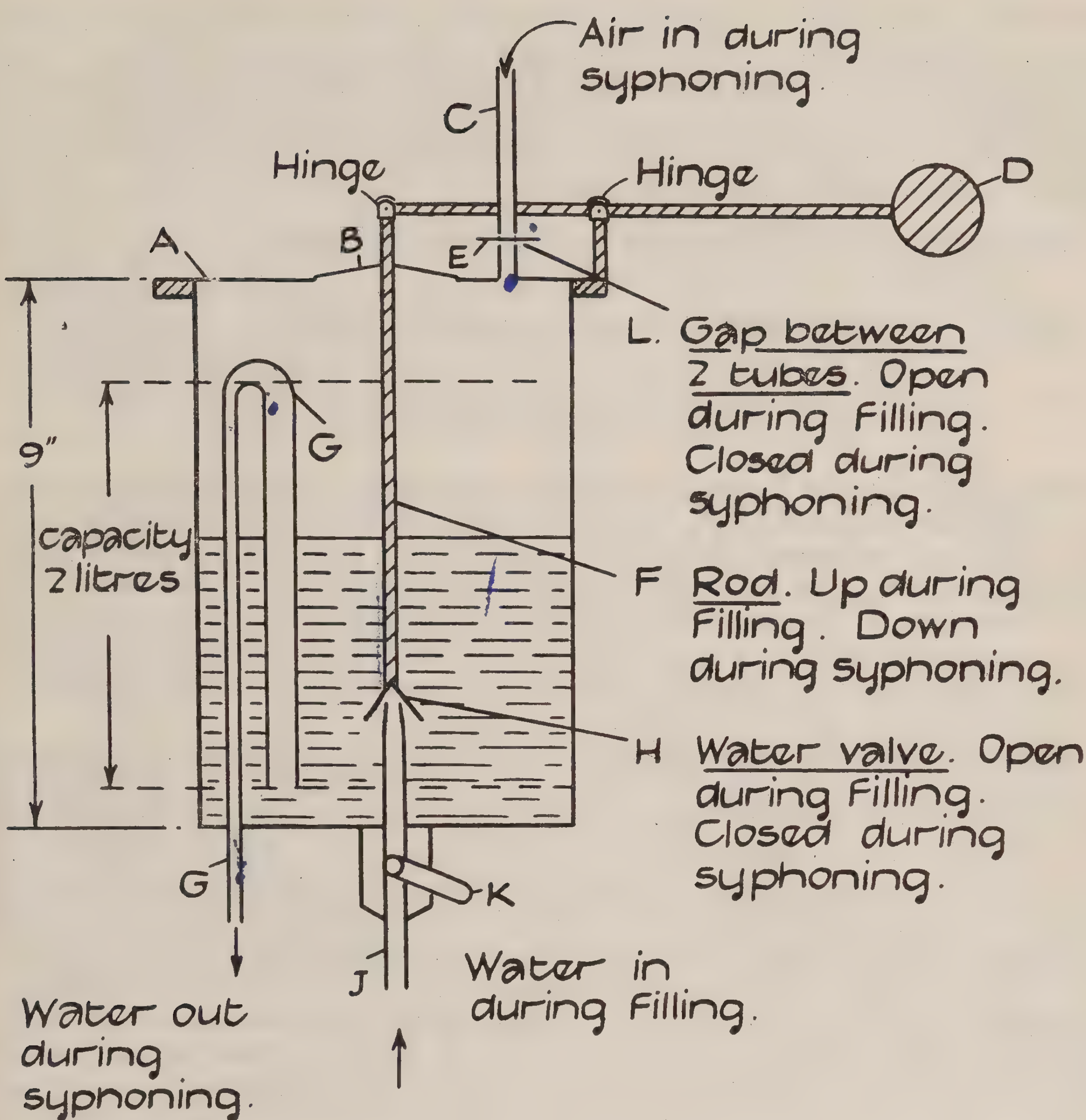




LEAD PEROXIDE APPARATUS WITH ULTRA-VIOLET DAYLIGHT INTEGRATOR.



Automatic Filtef.



- A Tank.
- B Leather diaphragm.
- C Air inlet tube.
- D Counterpoise.
- E Filter paper. Rotated by clock during filling. Clamped at L during syphoning.
- F Central rod.
- G Syphon (Water outlet).
- H Water valve.
- J Water inlet pipe.
- K Control valve.
- L Tube clamp.
- M Stand.
- N Dust cover.

Automatic Filter.
Details of operation—simplified.

conversion, for Leicester readings, is about 12%. The calibration curve, given in Fig. 2·31, represents average conditions accurately to about 5%, but may also have an unknown persistent error. This curve is valid only for the particular photometer used in Leicester, and to compare the Leicester calibration with those of other observers a calibration of the visual method was also made, using Owens' Scale of shades. The result was:—

Mass of solid matter in a 1-in. circle of Owens' shade 1 (Leicester calibration)	0·059 mg. (S.E. ±7%)
Ditto (J. G. Clarke's original calibration for automatic filter)[3] ..	0·041 mg.
Ditto (A. S. G. Hill)[11]	A. 0·037 mg. B. 0·033 mg.

A. Based on shades of scale reading 20.
B. Based on shades of scale reading 2.

In 1943 at Teddington it was found that, to stain Whatman No. 1 filter paper to a given Owens' shade, 13% more smoke was required than to do the same with standard automatic filter paper. This would account for part of the difference between the above calibrations. Other differences may be because the calibrations at Leicester were made on normal Leicester air, whereas the other two calibrations were made respectively on London air and on artificial smoke. Unfortunately, changes of programme resulting from the outbreak of war prevented any further investigations at Leicester.

The broad outline of the method used in Leicester for obtaining the calibration of Fig. 2·31 was as follows:—With a special method of using an ordinary balance, known as Conrady Weighing[12], it was found possible to weigh Jena sintered filters with a standard deviation of 0·05 mg. Jena sintered filter No. 4, size of pores 5 to 10 microns, was found to retain all the smoky matter from air drawn through it at 30 to 250 cu. ft. per day. Arrangements were made to pass Leicester town air in winter through two such filters in parallel at rates of about 200 cu. ft. per day, there being no funnel or other connection on the inlet side of the filters. At the same time air from the same source was passed through three smoke filters at rates of from 7 to 60 cu. ft. per day. After runs of 3 to 5 days the increase in weight of the sintered filters was determined, care being taken to bring the filters to the same hygrometric condition for each weighing, and optical readings were made on the smoke filters. The weights of material collected in the sintered filters varied from 0·8 to 3·5 mg., and the standard deviation of one weighing was about 10%. The standard deviation of one optical reading was about 12% on the mass-scale. The standard deviation of the final estimate of the weight on a 1 in. circle of unit optical reading was estimated at 7%. This was the result of 10 runs of 3 to 5 days each.

Distinct from the above calibration were experiments to determine the shape of the calibration curve. Twelve smoke filters were run in parallel for periods of three days at widely different pumping rates ranging from 3 to 100 cu. ft. per day. The weight of dust on a single filter paper was then taken as proportional to the volume of air passed. (This procedure is permissible if the different rates of pumping do not affect the efficiency of smoke sampling. Evidence that this is so is given in Section 2·322.) A single run of three days gave an estimate of the shape of the calibration curve against an arbitrary mass scale. In all, four runs were made.

The two experiments were combined to give the calibration curve of Fig. 2·31. On the smooth part of the curve the estimated standard deviation of the curve is 5%; the broken part is less accurate. Thus, when a measurement of smoke concentration in Leicester is given as x mg. per m.^{3}, it means that x mg. per m.^{3} would have been collected by a Jena sintered filter with one end open to the air, the rate of pumping being about 200 cu. ft. per day. It is important to remember this point in connection with Section 2·322.

2·32 *Limitations of the Smoke Filter*

2·321 *The nature of suspended matter* is well worth consideration, because of its differences from deposited matter. The size-distribution of deposited matter will be more or less the same as the size-distribution of particles emitted by the chimneys. (Near chimneys, however, the deposit will contain relatively more large particles, and conversely. There are also the limitations of Section 2·21.) The size-distribution of suspended matter will be very different, because small particles remain in the air longer than large particles. Assuming Stokes' Law of fall, the time of fall of a spherical particle is inversely proportional to the square of its radius; suspended matter must therefore include a much greater proportion of small particles than emitted or deposited matter.

The difference is not merely one of size-distribution, for there can be a well marked difference in composition, as the following table shows:—

Deposited and Suspended Matter in the Centre of Leicester during October, 1938

	Suspended Matter % by weight	Deposited Matter % by weight
Tar (soluble in CS_2)	14	1
Other combustible matter ..	71	30
Ash	15	70

These results are for Leicester, where there are both domestic and factory fires. They would be expected to apply to other towns where coal is put to industrial and domestic use in about the same relative proportions. From the table it follows that:—

(i) Suspended matter (the lighter particles of emitted matter) is mainly combustible.

(ii) Deposited matter (the emitted matter as a whole) is mainly ash.

Finally, it is of interest to consider the general characteristics of domestic and industrial combustion of coal. The following information was supplied by the Fuel Research Station:—

Average conditions of domestic and industrial combustion of coal

	Domestic Grates	Industrial Furnaces
Efficiency of combustion ..	Poor	Good
Velocity of flue gases ..	4-6 ft/sec.	5-40 ft./sec.
Combustible matter dispersed in flue gases	80%-90% of dispersed solids	2%-50% of dispersed solids
Ash dispersed in flue gases	20%-10% do.	98%-50% do.

It is clear that:—

(iii) Domestic particles must be fairly light, because domestic flue gases, with their low velocity, will not carry heavy particles up the chimneys.

(iv) Industrial particles may be light or heavy.

(v) Domestic particles are mainly combustible matter.

(vi) Industrial particles are mainly ash.

Now if domestic fires, as well as industrial furnaces, make an important contribution to atmospheric pollution, statements (i) to (vi) can be summarized as:—

(vii) Suspended matter is mainly domestic combustible matter.

(viii) Deposited matter is mainly industrial ash.

There are good reasons for thinking that both domestic and industrial sources do in fact contribute substantially in Leicester and other towns. One reason is that similar amounts of coal are burned industrially and domestically. Other reasons appear in Sections 3·411, 4·2 and 4·3. Conclusions (vii) and (viii) are there ore worthy of note, but they may not apply to all towns—for example, to Cardiff, where there is relatively little smoke because of the nature of Welsh coal. The best experimental test might be to "label" the solids escaping from definite chimneys by adding to the fuel something distinctive which would not be destroyed in the fire and would attach itself to the solids. Thus, if there were not objections, on other grounds, to their use, radium salts might be added. The labelled solids could then be sought in deposits and in smoke filte s by very sensitive radiometric methods. In any case, it is important to recognize that the smoke filter and the deposit gauge may measure pollution from different sources.

2·322 *Efficiency of sampling with the smoke filter*. The size-distribution of smoke is a subject which still requires investigation. Green[13] gives estimates for five industrial dusts from which it can be inferred that 50% by weight of such dusts is less than 3 to 10 microns (0·0003 to 0·001 cm.), and 80% is less than 5 to 15 microns in mean diameter. These results depend to some extent on the nature of the dust. Atmospheric smoke may be similar in size-distribution, but a direct investigation is still needed.

The smoke filter, from considerations of the size of the inverted funnel (3 in. diameter) and the average pumping rate (50 cu. ft. per day), will catch relatively few particles whose rate of fall is greater than about 0·01 ft. per sec. This is the velocity of fall of spherical water droplets of diameter 10 microns, the smallest water droplets usually found in fogs, and thus the inverted funnel adequately serves its chief purpose of preventing too much water from getting into the apparatus. Making allowance for the greater density of suspended particles, and for their more irregular shape, the maximum size of particle entering the smoke filter would also be of the order of 10 microns. Particles of twice this size would enter the Jena sintered filter used in calibrating (Section 2·31).

From the considerations of the last two paragraphs, the pumping rate of the smoke filter should not very much affect its efficiency of sampling. This was shown to be so at Leicester by a series of eight experiments, in which two smoke filters were compared whose pumping rates were very different. A filter pumping at 225 cu. ft. per day gave an average of 1½% higher estimates of smoke concentration than a filter pumping at 30 cu. ft. per day. The standard error of the determination was 3%, so that no significant difference in the estimates was established. A second series of experiments showed that if the sampled air was drawn at 30 cu. ft. per day through 12 ft. of horizontal glass tubing of ¼-in. diameter bore, there was no appreciable loss of smoke by settlement inside the tubing. It was found, however, that smoke was deposited at sharp bends and kinks in the glass and rubber tubing leading to the apparatus. A simple test showed that such deposition was not likely to be a centrifugal effect, but was chiefly caused by turbulence of the air stream. Bends of more than 1 in. radius of curvature were found to be satisfactory.

The smoke filter, therefore, is an efficient instrument for sampling suspended matter in the air of Leicester, because there are not enough particles of sizes greater than 10 microns to matter. The smoke filter would need modification to make it efficient in regions where there are many large particles—for example, within a few yards of a chimney stack.

2·323 *Errors of observation* arise in three ways, because an estimate of the average concentration of smoke in the air at one place, during one period of 24 hours, needs three observations. These are a reading of the volume of air

sampled, an optical reading of the blackness of a smoke stain, and a calibration curve to convert the optical reading to the mass of material in the smoke stain. Dry gas meters of the ordinary domestic type were used in the Leicester Survey for measuring the volume of air sampled, and these were found to have small persistent errors of the order of $\pm 1\%$ or 2%. Such errors might possibly have been allowed for, but they were so small that it was decided to ignore them.

By running two smoke filters at the same place, in conditions as nearly identical as possible, the casual error of sampling, combined with the casual error of reading the optical density of the stain, was found. The effect of these errors on the final estimate of smoke concentration in mg. per m.^{3} was to give a standard deviation of about $\pm 6\%$ for 1 in. circular stains of weight 0·1 to 1·0 mg. Outside this range standard deviations were higher.*

By running two smoke filters in the same place at very different speeds (3 to 100 cu. ft. per day) an extreme estimate of the total casual errors of observation was made. This estimate would of course include any errors due to incorrect shape of the calibration curve. The standard deviations observed were from 10% to 15% when the mass of smoke on a 1 in. stain was between 0·05 and 0·3 mg., but greater outside this range. Steps were taken at Leicester by using two sizes of filter paper clamp, 1 in. and 2 in. diameter, to ensure that as many stains as possible were within this range of smokiness. It may be taken then, that

> daily estimates of smoke concentration have a standard deviation of not more than 15%.

The accuracy of the method may not be as high as was hoped, but for many purposes it is quite good enough. For instance, the standard error of a monthly mean, on the basis of 15% for individual observations, would be 3%. The day-to-day variation of smoke concentration is also very big indeed, occasions being quite common when one day's concentration was two to four times the concentration of the previous day.

2·324 *Persistent errors.* It is evident from Section 2·31 that the calibration curve used for conversion of optical readings to weights may be in error by some constant factor. Hence all smoke filter results of the Leicester Survey may be too high or too low in a fixed, but unknown, proportion. If the absolute concentration of smoke played an important part in discussions of atmospheric pollution, this would be serious, but as a matter of fact it plays practically no part in this report. It is sometimes used, however, to convey to the public the seriousness of atmospheric pollution, and for this purpose accurate absolute values are desirable. The discussions in this report, dealing with distribution, periodic variations and correlation with weather conditions, are not affected, since only ratios of concentrations at different places or times are involved.

Another type of persistent error would affect discussions of the distribution of smoke, but not periodic variations or correlation. An example of this type would be a defective gas meter at one of the survey stations, which would give persistently high or low results for one station only. The ordinary gas meter errors at Leicester were found to be negligible, and serious defects in gas meters were quickly found and put right. A more problematical error of this type is the possibility that the calibration curve for a town may differ from that for a country district. Fig. 2·31 was made from town observations. It had been intended to repeat the calibration at a country station, but the war prevented this.

There is one guide, however, to the possible outcome of such a calibration. In Section 2·321 smoke was found to consist of 85% sooty and tarry matter

* Experiments were also made on the visual method of reading stain densities, by comparison with the Owens' Scale of shades, although this method was not used for normal routine work. It was found that the personal equations of different observers might produce persistent errors of as much as 10% on the final estimate of the weight of the smoke stain.

and 15% ash, even in Leicester where industrial chimneys would be expected to produce a high proportion of ash. (The gas works and power station are ½ mile to the south-west of the site of this analysis, and a Lancashire boiler, fired by wood shavings, is 350 yards to the north-west. The collection of the sample lasted a month during which S.W. winds blew for 19 days and N.W. winds for 2 days). In the country, smoke would probably have a higher rather than lower proportion of sooty and tarry matter than in the town, and it does not seem likely that the calibration curve would be very different. However, until this matter has been properly investigated it must be considered a possible limitation of the smoke filter apparatus.

2·33 *Suggested Modifications*

For rough general purposes the type of smoke filter used on the Leicester Survey, described in Section 2·3, is quite satisfactory. Unless the readings of many different observers are to be compared to within 10%, there is no reason why the Owens' scale of shades should not be used. This scale is already standardized and on the market. It is cheap and simple to use compared with photometric methods of reading. The apparatus in this form, then, is very suitable for use by municipal and other bodies who are investigating pollution. No modifications at all are recommended where the apparatus is to be used in industrial areas. In country districts it would be advisable to have a minimum pumping rate of 100 cu. ft. per day, or in some places even higher.

When an accuracy higher than 15% is wanted in estimating smoke concentrations, or where accurate absolute results are required, the use of filter papers for absorbing smoke should be abandoned. Filters made of asbestos fibres, packed in aluminium tubes, were found to be perfectly efficient absorbents of smoke particles. Because they could easily be dried in an oven, and kept dry by plugging the ends, they were weighable with great accuracy. They could deal with samples of 500 cu. ft. of air per day, but were not tested at higher pumping rates. Such filters, working at 1000 cu. ft. per day, would give weights of smoke above 1 mg., and could be weighed either on a microchemical balance or an ordinary balance adapted for Conrady weighing.

2·4 The Automatic Filter

This instrument was designed by Dr. J. S. Owens[4] in 1918 to take regular samples of smoky matter from the air, at intervals of an hour or less, and it has been widely used ever since. The instrument is connected to a water supply, and a chamber automatically fills with two litres of water and empties again, the full cycle of operations occupying from ¼ to 1 hour. As the chamber empties, air is drawn through a piece of white blotting paper, leaving a circular smoke stain of ⅛ in. diameter. The instrument is arranged to give 24 or more of these smoke stains per day, and requires attention only once daily. Each stain represents the smoke in two litres of air. By visual comparison with a standard scale of shades (already mentioned in Section 2·3), an estimate of the shade intensity can be made; with the aid of the calibration printed on the scale of shades this may be converted to an estimate of smoke concentration in mg. per m.^{3} of air. The printed calibration is that of J. G. Clarke, and is given for a 1-inch stain in Section 2·31.

In normal use the chamber of the automatic filter empties in about a quarter of an hour, which is equivalent to a rate of flow of air of about 7 cu. ft. per day. At Leicester it was found that the smoke stains were usually too light for accurate estimation, and the area of each stain was therefore reduced to one-third. The effect of this was to cut down the rate of air flow to about 4 cu. ft. per day. Hence the automatic filter may be less efficient than the smoke filter for sampling smoke particles. The same type of funnel and inlet tubing was used at Leicester for both instruments.

2·41 *Limitations of the Automatic Filter*

All the limitations of the smoke filter discussed in Sections 2·32 to 2·324 are applicable to the automatic filter. The casual error of observation of the automatic filter will indeed be higher, because of the small area of stain. This does not seriously interfere with the utility of the automatic filter as a standard instrument for measuring atmospheric pollution; for in a single winter day shade readings ranging from 1 to 10, and more, are frequently found. If the automatic filter is required for use in country conditions, it should be modified so as to draw in at least 10 litres of air at each complete operation. There is in existence a type of automatic filter where the volume of air through each stain can be adjusted at will, but it is much more expensive than the standard type.

2·5 Volumetric Sulphur Dioxide Apparatus

Within the limitations which are discussed below, this instrument measures the mean daily concentration of sulphur dioxide in the air. Air from outside a building is drawn at the rate of about 50 cu. ft. per day through a bubbler, the volume of air being measured by a gas meter. The bubbler contains about 40 c.c. of dilute hydrogen peroxide (1 vol.), whose *p*H has been adjusted to 4·5. Sulphur dioxide is removed from the air by the reaction

$$H_2O_2 + SO_2 = H_2SO_4$$

At the end of a day's run the sulphuric acid in the bubbler is estimated by titrating to *p*H 4·5 with N/250 sodium hydroxide, using B.D.H. 4·5 indicator. The mean concentration of sulphur dioxide in the air during the run is then

$$\frac{1{\cdot}582 \times \textit{c.c. of alkali}}{\textit{cu. ft. of air}}$$ volumes of sulphur dioxide per million volumes of air.[5]

The volumetric sulphur dioxide apparatus has been used as a routine instrument for measuring atmospheric pollution by municipal and other bodies since 1931. It can conveniently be combined with the smoke filter apparatus (Section 2·3) by passing the sampled air first through the smoke filter and then through the hydrogen peroxide bubbler.

2·51 *Limitations of the Volumetric Sulphur Dioxide Apparatus*

2·511 *Effect of combining with the smoke filter.* The combined apparatus was used throughout the Leicester Survey, since it had previously been found practicable to combine the two without serious mutual interference. In 1935 experiments had been started in Sheffield, Hull, and Glasgow to determine whether the presence of a smoke filter might upset estimates of sulphur dioxide. In each city two sets of volumetric apparatus were used side by side, identical except that one of them incorporated a smoke filter apparatus. The experiments showed that the smoke filter produced a slight loss of acidity, amounting to 1% to 4%. The highest monthly average loss, expressed as a concentration of sulphur dioxide, was 0·005 part per million. Such losses were not considered a serious objection to the combined form of apparatus. The losses of sulphur dioxide may be due to (1) absorption of sulphur dioxide by the filter paper or (2) evaporation from the filter paper of ammonia which would then be caught in the bubbler.

Investigation of such small losses is difficult, but from laboratory tests using twelve filter papers in series explanation (1) seemed more probable. If explanation (1) is correct, the losses of sulphur dioxide will be a nearly constant percentage rather than a nearly constant amount. Provisionally, then, it may be assumed that the effect of the smoke filter is to reduce estimates of sulphur dioxide by not more than 4%.

2·512 *Other contaminants and absorbents.* In addition to the filter paper and clamp, the incoming air passes through a glass funnel, at least four feet of glass

tubing, and six to twelve inches of rubber tubing. The liquid in the bubbler washes the dipping glass tubing and the inside of the bubbler, and it may also come into contact with the rubber bung. At Leicester it was necessary to remove the bubblers daily from the sites of observation to the laboratory, and corks were used which might also conceivably contaminate the liquid.

It was found soon after starting the Leicester Survey that every one of these appurtenances was liable to affect estimates of sulphur dioxide concentration. New rubber, cork, and filter paper all contain ammonia, and will reduce the acidity of liquids which wash them. Air passing through rubber tubing will lose some of its sulphur dioxide. Soft glass will make water which washes it alkaline, and new hard glasses make the water slightly acid. Air passing through soft glass tubing loses some of its sulphur dioxide, but hard glass tubing is satisfactory. Hard glass bubblers, too, were satisfactory after steaming or running-in.

Contamination and dry absorption were serious enough, before they were discovered, to upset a number of experiments. They were avoided at Leicester by using hard glass, and by waxing soft glass, rubber tubing and cork. The insides of the smoke filter clamps also were either waxed or enamelled.

2·513 *Interpretation of readings.* If sulphur dioxide were the only soluble impurity in the atmosphere, there would be no doubt that the volumetric apparatus determines the concentration of sulphur dioxide. It is known, for instance, that hydrogen peroxide is a most efficient absorbent of sulphur dioxide in much more stringent conditions than those described in Section 2·5. But there are known to be certain constituents in the air which are soluble in water, and which may make the water more acid or alkaline. It is not proposed here to consider such abnormal constituents as hydrochloric acid, which may occur near chemical works, but to confine attention to soluble impurities which may occur in any town.

The chief of these soluble impurities is carbon dioxide, but this forms such a weak acid that its effect is eliminated by using the method described, involving titration to *p*H 4·5. Air containing ordinary concentrations of carbon dioxide, when bubbled through water at ordinary temperatures, produces a *p*H of 5·0 to 5·5, depending on the concentration of carbon dioxide and the temperature. It can be shown that such air, when bubbled through a very dilute acid of *p*H 4·5, changes the *p*H to a value between 4·46 and 4·496. Such changes are negligible, having no effect on the indicator used.

Sulphuric acid is known to be suspended in the air of industrial districts in minute quantities. Coste and Courtier[14] found it in concentrations of about $\frac{1}{100}$th of that of sulphur dioxide, but theoretical considerations suggest that only a very small proportion of the sulphur caught in bubblers is sulphur trioxide. Sulphuric acid mist can be blown through caustic potash solution and it emerges as a cloud. The question, however, is of no practical importance here, because an accuracy of 5% for each determination of sulphur dioxide would be enough.

Small concentrations of ammonia gas have been found in the atmosphere. Ammonia is very soluble in water, and is nearly completely caught by a standard bubbler containing slightly acid water or hydrogen peroxide. Being an alkali, its presence would reduce estimates of sulphur dioxide. It may be given off from sewage, animal refuse, and decaying vegetation, or it may be formed during incomplete combustion of coal. The concentration of ammonia in central Leicester seems to be rather lower than in the suburbs and surrounding country, and thus it appears that coal is not likely to be the chief source of atmospheric ammonia.

It is not known how much of the ammonia in the air is already combined with sulphur dioxide (and water), and how much remains free, but both forms have been detected. Combined ammonia cannot interfere with estimates of the

concentration of sulphur dioxide, whereas free ammonia does. The total ammonia (combined and free) caught by a standard bubbler can be determined very accurately by the Nessler method, and such determinations represent the upper limit of the possible amount of free ammonia. The concentrations of free ammonia in the air of Leicester have been found in this way to be not more than 0·01 part per million. The effect of 0·01 part per million of free ammonia in the air is to reduce estimates of sulphur dioxide by 0·005 part per million, since 2 volumes of NH_3 neutralize 1 volume of SO_2. It will therefore be the practice in this report to assume ammonia to be present at the concentration of 0·002 part per million, and, after correction, to express concentrations of sulphur dioxide to the nearest 0·005 part per million.

To affect plants, animals, and materials, sulphur dioxide must usually first go into solution. But ammonia, being more soluble, is likely to be there first. Hence the sulphur dioxide in solution will probably have to neutralize this ammonia before the rest of it can attack other substances or be oxidized to sulphuric acid. Therefore the volumetric apparatus, uncorrected for ammonia, probably does not underestimate the effective sulphur dioxide. In this report, the volumetric method will usually be considered as a slightly inaccurate method of determining sulphur dioxide. The inaccuracy is important in country districts in summer, but not at other times or places.

2·514 *Casual errors*. Observations of sulphur dioxide concentrations are closely reproducible, in the sense that two sets of apparatus at the same place will give nearly the same results. In such circumstances the standard deviation of a single observation has been variously estimated at from 0·001 part per million in summer to 0·005 part per million in winter, or about 3% of the average concentration of sulphur dioxide.

The volumetric sulphur dioxide apparatus could be developed into a particularly accurate method of observing atmospheric pollution. By taking special precautions and by modifying the design, casual errors could probably be reduced to 0·0001 part per million. Such accuracy would, however, be useless without a knowledge of the concentration of free ammonia in the air.

2·515 *Summary of limitations of the volumetric sulphur dioxide apparatus.* Provided that care is taken to avoid contamination and absorption of sulphur dioxide, the form of apparatus described in Section 2·5 is quite satisfactory for use in towns where only moderate quantities of chemical fumes are produced. A smoke filter may be incorporated, and no correction for atmospheric ammonia need be applied if the estimated concentration of sulphur dioxide is expressed to the nearest 0·005 part per million. The apparatus should not be used where the air is likely to be contaminated by local sources of ammonia or acid fumes. As the errors due to ammonia and the smoke filter are persistent, always reducing estimates of the concentration of sulphur dioxide, the mean of a large number of observations will not be very much more accurate than an individual observation. Means therefore should also be rounded off to the nearest 0·005 part per million.

If greater accuracy is required, or if it is desired to determine sulphur dioxide in the presence of higher concentrations of ammonia, special precautions are necessary. No smoke filter should be incorporated, and steps should be taken to determine the concentration of free ammonia in the air. Laboratory experiments with mixtures containing 1 to 10 parts per million of sulphur dioxide and ammonia have shown that the concentrations of free sulphur dioxide and free ammonia can be determined by volumetric methods. Preliminary attempts to analyse lower concentrations in the same way were less successful.

2·52 *Hourly Volumetric Sulphur Dioxide Apparatus*

In 1936 Mr. E. W. Jackson, of Middlesbrough, presented to the Atmospheric Pollution Research Committee a device for taking hourly samples of sulphur

dioxide. The device is a spring-loaded multiple tap, controlled by a clock, and arranged to turn on in succession 24 bubbling tubes, each tube being open for one hour. The bubbling tubes contain dilute hydrogen peroxide of *p*H 4·5, and air is drawn from outside through whichever tube is open. Thus the apparatus is a modified form of volumetric sulphur dioxide apparatus, for determining hourly mean concentrations of sulphur dioxide. The 24 tubes are titrated daily and recharged with dilute hydrogen peroxide.

In December, 1937, the hourly volumetric sulphur dioxide apparatus was set up in Leicester, in the laboratory at 59, Regent Road, and used continuously until December, 1939. The intention was to observe the diurnal variation of sulphur dioxide concentrations, to supplement the observations of hourly smoke concentrations which were made with the automatic filter.

2·53 *Limitations of the Hourly Volumetric Sulphur Dioxide Apparatus.*

Apart from minor mechanical troubles, no difficulties were met in using the apparatus at Leicester which had not previously arisen with the standard apparatus described in Section 2·51. The only possible new sources of error were the increased rate of pumping and chemical action of the multiple tap. The rate of pumping was about 500 cu. ft. per day, and the quantity of dilute hydrogen peroxide was limited to about 20 c.c. by considerations of space. Careful tests showed, however, that no sulphur dioxide passed the bubblers under these conditions, since none could be caught in much more efficient types of bubbler placed after them. The multiple tap was in the form of a brass turn-table, and powdered graphite was used as a lubricant for it. It was found to have no appreciable chemical action on the air or sulphur dioxide passing through it.

The limitations of the hourly volumetric sulphur dioxide apparatus are therefore identical with those already discussed in Sections 2·51, excluding Section 2·511.

2·6 Lead Peroxide Method

An entirely different way of measuring sulphur dioxide in the air is based on the facility with which gaseous sulphur dioxide combines with the solid lead peroxide to form lead sulphate, the reaction being

$$SO_2 + PbO_2 = PbSO_4.$$

Since lead peroxide and lead sulphate are both insoluble in water, the practice is to leave a prepared surface of lead peroxide in the open air for a month, after which the weight of sulphate in it is determined analytically. Other things being equal, the yield of sulphate has been shown to be proportional to the mean concentration in the air of sulphur dioxide. The reactivity of lead peroxide with sulphur dioxide might be expected to depend on wind force and direction, rainfall, humidity, and temperature, and on the texture of the exposed surface. Some of these possible difficulties are met, for comparative purposes, by adopting the recommended standard procedure,[6] which has been used throughout the Leicester Survey. Others have been examined in laboratory and field experiments by B. H. Wilsdon and F. J. McConnell,[7] who originated the method.

The standard procedure for using the lead peroxide method is to wrap a piece of tapestry cloth 10 × 10 cm. round a standard porcelain cylinder. A paste containing gum tragacanth and 8 g. of lead peroxide from a special stock is applied evenly to the tapestry surface and allowed to dry in a desiccator. The prepared cylindrical surface of lead peroxide is exposed to the air, usually for one month, by mounting the porcelain cylinder upright on a 4′ 6″ wooden stand. It is partially protected from rain by a cowl of standard dimensions. Analysis for lead sulphate after exposure is made by a standard method. Results are not converted to units representing the mean concentration of

sulphur dioxide in the air during the exposure, but are expressed as milligrams of sulphur trioxide per day per 100 sq. cm. of lead peroxide surface. If results in these units are multiplied by 0·025, a very rough estimate will be obtained of the mean concentration of sulphur dioxide in volumes per million. It was found at Leicester that the ratio of the sulphur dioxide concentration to the rate of sulphation of lead peroxide varied from site to site between 0·01 and 0·04. This variation has not yet been satisfactorily explained, but it has been confirmed by measurements in other parts of Great Britain.

2·61 *Limitations of the Lead Peroxide Method*

2·611 *Casual errors.* Three lead peroxide cylinders were exposed monthly at the City General Hospital, Leicester, from September, 1937, to April, 1938. The mean yield was 1·40 mg. SO_3 per 100 sq. cm. per day, and the estimated standard deviation of one estimate was 0·135 mg. SO_3 per 100 sq. cm. per day. The City General Hospital is in a clean situation about two miles from the centre of Leicester. Similar tests in other districts or at other times would necessarily give different results, and the above figures are not of general application.

For want of more detailed evidence, it will be considered that the casual errors of the method produce a standard deviation of about 10%. These casual errors are made up of differences in preparation and exposure of the cylinders, sampling errors, and errors of analysis.

2·612 *Interpretation of readings.* A simple way of describing results by the lead peroxide method is to consider them as estimates of the mean "activity" of sulphur dioxide in the air. This is convenient when studying the decay of building materials. The assumption is that, whatever may be the effects of wind force and direction, rainfall, humidity, and temperature, the rate of reaction with lead peroxide provides an integrated measure of the chemical activity of sulphur dioxide in the vicinity. Thus the "activity" can serve as a basis for comparing the conditions to which calcareous building stone, and other materials liable to react with sulphur dioxide, are exposed in different districts or at different times.

This report is not primarily concerned with the decay of building materials; it is concerned with the concentration of various forms of pollution in the air. If possible, therefore, it would be very helpful if results by the lead peroxide method could be interpreted as estimates of the mean concentration of sulphur dioxide in the air at the time and place of the observation. This will be shown to be approximately true, as regards distribution and annual variation, but to be untrue of irregular month-to-month variations because the factors of turbulence and rainfall, which decrease concentrations of sulphur dioxide, appreciably increase its rate of reaction with lead peroxide.

In spite of this limitation, the lead peroxide method will clearly be of use for measuring in arbitrary units the distribution of sulphur dioxide in the air in and near a single town. For the weather conditions, averaged over a month, do not differ appreciably over an area of a few square miles, while the concentration of sulphur dioxide may differ very considerably.

2·613 *The effect of weather on the lead peroxide method* was mentioned in Section 2·6. Although a number of aspects of weather—namely, wind, temperature, humidity, turbulence, and rain—might seem likely to affect the reactivity of lead peroxide cylinders, only rain has been shown at Leicester to have an appreciable effect. (Reactivity is defined as rate of production of sulphate, divided by concentration of sulphur dioxide in the air.)

Wind direction is considered to have no effect on reactivity, because the lead peroxide cylinder is exposed so as to present a similar aspect to all winds.

Wind force (u), from statistical considerations, using results for 26 months

from the four central stations at Leicester, did not have any significant effect. This is in contradiction to the result with wind-tunnel experiments of Wilsdon and McConnell,[15] who suggest that the reactivity is proportional to $u^{\frac{1}{4}}$. If this had been true at Leicester, then there should have been a significant positive regression of monthly mean reactivity on monthly mean wind velocity. The regression which was found from the aforementioned 26 months' records was not significantly different from zero, and was in any case of the wrong sign. The chances that this was an unlucky estimate of a regression in true accord with a $u^{\frac{1}{4}}$ law are about 1 in 50,000. It is possible that Wilsdon and McConnell underestimated the difficulties of producing average climatic conditions in a wind tunnel. The matter requires further investigation.

Temperature. Wilsdon and McConnell,[15] from theoretical considerations, showed that temperature had a small effect, a rise of 1° C. increasing the reactivity by about 0·4%. Seasonal changes of temperature in the British Isles should then cause a slight annual variation in the reactivity of lead peroxide cylinders, of amplitude about 5%. This could not be detected from the Leicester Survey results (Section 4·84), although there are indications in Table 4·21 that the yearly cycle of lead peroxide results is greater in range than that of volumetric sulphur dioxide determinations.

Relative humidity. From 22 months' observations at four stations in central Leicester, it did not appear that there was any significant correlation of relative humidity with reactivity.

Rainfall was found from 26 months' observations at four stations in central Leicester to have a correlation of +0·64 with reactivity, rainfall being measured by quantity in inches per month. With number of days on which rain fell per month (a rough measure of the duration of rain per month), the correlation coefficient of reactivity was +0·76. Thus there is a significantly greater reactivity in rainy months. In a month with 10 more rainy days than normal, from considerations of regression the rate of reaction is 22% faster than normal. (The standard deviation is about 6 rainy days per month, and a deviation of 10 days or more occurs about once in 10 months on an average.)

In the laboratory, tests were made to compare the reactivity of dry lead peroxide cylinders with wet ones, which were kept wet by a wick dipping in a beaker of distilled water. It was difficult with simple apparatus to keep the degree of wetness constant, and the results varied considerably. The wet cylinders absorbed from 10% to 90% more sulphur dioxide than the dry cylinders. It is therefore well established that wetness promotes the reaction between lead peroxide cylinders and sulphur dioxide. It so happens, however, that rain reduces the concentration of sulphur dioxide in the air (see Section 4·74). Thus at times when the reactivity of lead peroxide with sulphur dioxide is high because the lead peroxide is wet, it usually happens that the available concentrations of sulphur dioxide are lower than normal. Of the two opposing terms, reactivity is the more powerful. The result is that the yield in milligrams of SO_3 per 100 sq. cm. per day has a small positive correlation with rainfall; with quantity of rain per month, from 27 months' observations in central Leicester, the correlation is +0·46. Thus while rain accounts for $(0{\cdot}76)^2 = 0{\cdot}58$ of the variance of reactivity of lead peroxide cylinders, it only accounts for $(0{\cdot}46)^2 = 0{\cdot}22$ of the variance of the yield of the cylinders. For comparison, the correlation between number of rainy days per month and concentration of sulphur dioxide, for a period of 35 months, was − 0·45. Rain therefore affects volumetric results and lead peroxide results in opposite directions, but in nearly equal magnitudes if standard deviations are taken as units.

It should be noted that the lead peroxide method could be much improved, from one point of view, by completely shielding the lead peroxide cylinders from rain, in a form of Stevenson screen made of materials which do not react with sulphur dioxide. The method would then no longer measure "activity" of

sulphur dioxide so well, but it would respond better to changes in emission of sulphur dioxide.

Turbulence is shown in Section 4·8 to have no significant connection with yield of lead sulphate. The reason for this, too, appears to be a balancing of increased reactivity against reduced concentrations.

2·614 *Effect of atmospheric ammonia.* Atmospheric ammonia has been shown to reduce estimates by the volumetric method of the concentration of sulphur dioxide, but it is unlikely to interfere with the lead peroxide method. Any sulphur dioxide reaching the cylinders will probably remain there, as lead sulphate, whether ammonia is present or not.

2·7 The Ultra-violet Daylight Integrator

One of the harmful effects of atmospheric pollution is to diminish the amount of sunlight reaching the earth. In the towns and cities of the British Isles there are many people whose health would be improved by additional sunlight. Although the chief reason for this is occupational, all townspeople would receive more sunlight if atmospheric pollution were eliminated, and it is therefore important to find out how much sunlight is lost because of atmospheric pollution. All ordinary sunlight is beneficial, but ultra-violet radiation of wavelengths 2900 to 3100Å is particularly so, because it helps the synthesis in plants and animals of vitamin D. Radiation of these wavelengths occurs in about equal intensities in skylight and direct sunlight.[16] Hence it is important to measure the daily amount of this radiation reaching the earth from the sun and sky.

At the start of the Leicester Survey there were various instruments for this purpose on the market, and it had been hoped to find one of them to be suitable for use at Leicester. It was intended to use about twelve instruments to determine the distribution of ultra-violet daylight received in and around Leicester. On investigation no suitable instrument was found. Rather than leave out daylight measurements from the programme, however, it was decided to design a suitable instrument. As far as possible, the instrument was required to have the following qualities:—

(1) It should require attention not more than once each day; it should be cheap and simple, and its records easy to read.
(2) It should be most sensitive to wavelength 3000Å or as near as possible. Visible light should not affect it.
(3) It should be equally sensitive to radiation from any part of the sky. (This would avoid the necessity of following the course of the sun, and also ensure that skylight should be faithfully recorded.)
(4) It should give a record of the total ultra-violet radiation received from all parts of the sky in one day.
(5) It should give a readable record on the dullest winter day and the brightest summer day with an accuracy better than 20%.

These requirements were approximately satisfied as follows. It was found that a coaxial arrangement of two translucent fused silica bulbs, necks downwards and one within the other, could be adjusted so that a constant intensity of diffuse light, within 5%, passed down the neck of the inner bulb, for any position of the source over a hemisphere.[17] (The source must be of constant intensity throughout the adjustment, and must be kept at a constant distance from the centre of the outer bulb.) This arrangement satisfies condition (3) above.

A thin deposit of silver on a fused silica quartz disc was used as an ultraviolet light filter. It was found to transmit a band of wavelengths from about 3150 to 3350Å. It also transmits a little visible light, but the effect of visible sunlight on an instrument incorporating a silvered filter was shown to be neglig-

ible. Uniformity of silver deposit could be obtained to within 10%. Such a filter therefore satisfies condition (2) approximately. The transmitted light is about 250Å longer in wavelength than was specified, and is outside the range of wavelengths which are strongly absorbed by atmospheric ozone.

Conditions (4) and (5) were satisfied by using an optical wedge to vary the intensity of the light, and gaslight photographic printing paper as a light indicator. The wedge was designed to transmit 500 times as much ultra-violet radiation at the thin end as at the thick end. By adjusting the thickness of

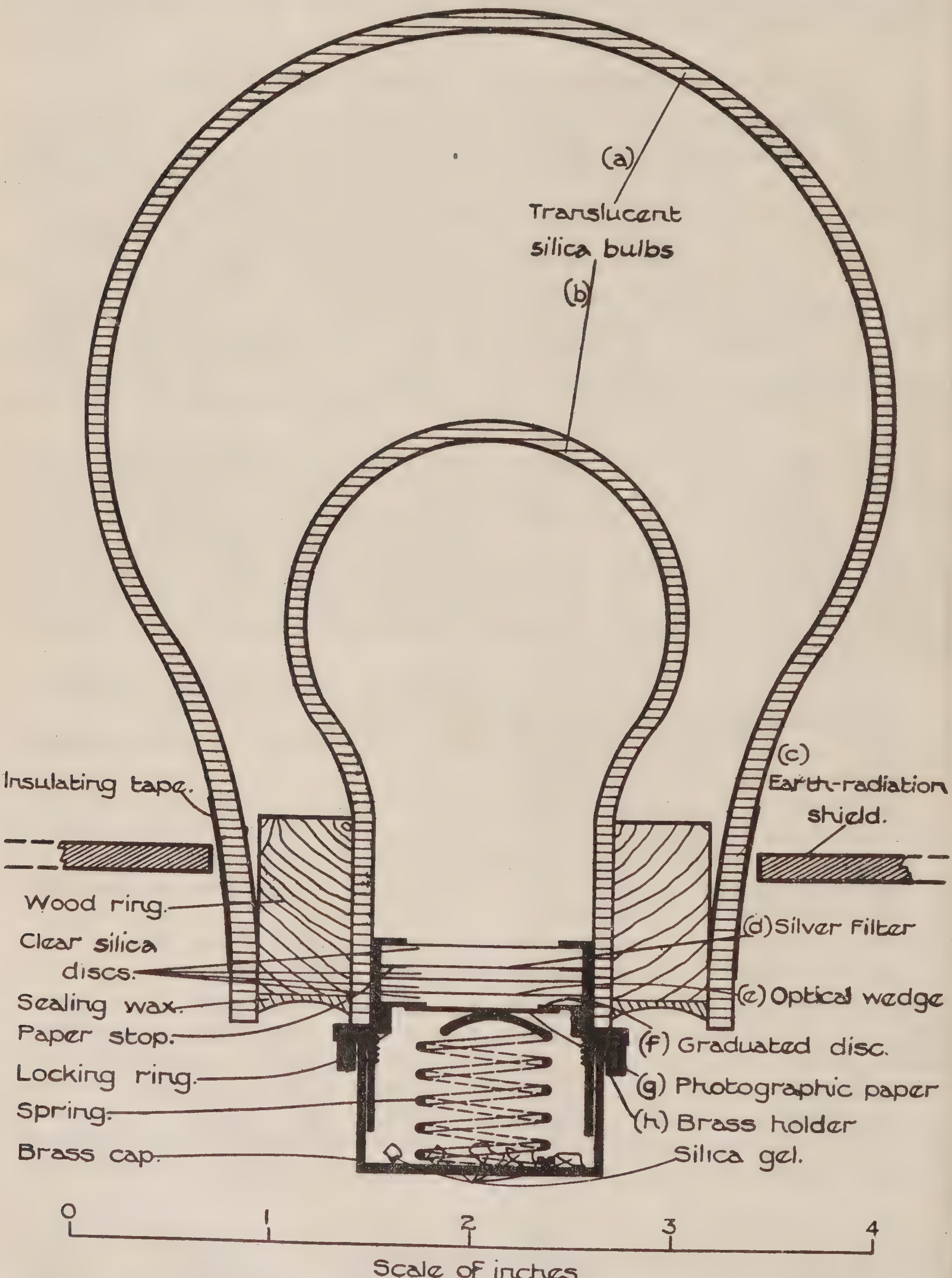


Fig. 2·7 Ultra-violet Daylight Integrator.

silver in the filter, and later by using different types of sensitive photographic paper, instruments were made to give a readable daily record over the whole range from midwinter to midsummer.

Fig. 2·7 is a diagram of the completed ultra-violet daylight integrator, of which 11 were used during the Leicester Survey. The instrument is placed in such a way that the outer translucent silica bulb (a) receives light from the sun and the whole of the sky. Radiation from the earth is cut off by the shield (c). A constant proportion of all light received passes downwards through the neck of the inner translucent silica bulb (b), and falls on the silvered silica window (d) of the brass holder (h). The ultra-violet light transmitted by (d) now passes through an optical wedge (e); for compactness, the wedge has been cast in an annular mould. The wedge is attached to a graduated disc (f), in contact with which is the photographic paper (g).

The instrument is exposed for a day at a time, after which the photographic paper is removed and developed by a standard process. The print shows a shadow of the graduated disc as far as the optical wedge has transmitted sufficient light to affect the photographic paper. (A specimen print is reproduced in the photograph of the lead peroxide apparatus with ultra-violet daylight integrator, following page 10.) The graduations which are visible down to an arbitrary standard shade are counted to estimate the total ultra-violet daylight received. In practice it was found possible to interpolate to half a division, so it was arranged for convenience to count each division as two units.

2·71 *Method of using the Ultra-violet Daylight Integrator*

As no description of the instrument has been published elsewhere, the purpose of this section is to put on record the standard method of using the ultra-violet daylight integrator which was adopted throughout the Leicester Survey.

The sites for the instrument all had a very open horizon. The average altitude of obstructions was nowhere greater than six degrees above horizontal. At each site the instrument was fitted to the top of the lead peroxide stand (Section 2·6), at a height of about five feet from the ground.

Exposure was for 24 hours, beginning each evening any time after one hour before sunset. The amount of daylight received between the time of loading and sunset was found to be negligible with this arrangement. A few granules of dry silica gel were placed daily inside the holder to keep the interior dry.

Development was with a standard commercial developer for one minute at a temperature of 65° F. The paper was fixed in acid hypo, and washed and dried. Development was carried out within two days of exposure, as there was some doubt about the stability of the latent image.

Reading the prints was by matching an arbitrary standard shade with the projecting graduations (Fig. 2·76a). The readings were then converted to those of an arbitrary standard apparatus by means of a calibration curve, which had been determined by exposing the two instruments together at the same site.

Corrections for horizon were still necessary in spite of precautions taken in choosing very open sites. The average altitude (A°) of the obstructions was measured, and A/3·6 units were added to the uncorrected reading. The divisor 3·6 was determined by exposing two instruments near to one another but with very different horizons. The corrections were always small, never exceeding two units. If they had been larger it might have been necessary to evaluate them more accurately, and to take into account the varying brightness of the sky.

2·72 *Limitations of the Ultra-violet Daylight Integrator*

2·721 *Conversion of readings to absolute units.* There is no commonly accepted standard unit of illumination for such light as is transmitted by a silver filter.

The most rigid way to specify the amount of ultra-violet light received by the integrator would be to use energy units, and give results in ergs. The labour of a determination in such units is great, however, and it is important to use a unit which is both easy to determine and easy to comprehend.

An object is defined as being under *standard natural u.v. irradiation* when it is receiving all possible light of wavelengths 3150 to 3350Å from the sun and sky, the sun being at altitude 45° and the sky being free from cloud and haze. Strictly, the object should be at sea level under normal atmospheric pressure, but altitudes of a few hundred feet and meteorological fluctuations of pressure may be tolerated. A *standard natural u.v. minute* is then one minute of such irradiation. Any other time interval may be substituted for the minute.

A possible objection to the standard natural u.v. unit is that the sun is not an ideal standard source, because it varies slightly. To investigate the importance of its variation, the correlation coefficient was considered between daily sunspot numbers and daily ultra-violet light values in the suburbs of Leicester. The result obtained was found to be not significant according to the definition of Section 6·12, and the sun was therefore assumed to be sufficiently constant for practical purposes. On the other hand Pettit[18], measuring the ratio of sunlight transmitted by a gold and a silver filter, found that the three-monthly mean intensity of solar ultra-violet radiation varied between 1·0 and 1·5 arbitrary units within seven years. J. R. Ashworth[19] has subsequently reached a similar conclusion. Clearly there is need of a satisfactory terrestrial standard of ultra-violet illumination. At the time of this investigation, however, no such terrestrial standard was available, and hence the natural unit was adopted.

In order to convert to standard units any reading with an ultra-violet daylight integrator, two instrumental constants must be known. These are the calibration of the optical wedge and the instrumental reading which is equivalent to one standard natural u.v. minute. Rather than determine these constants individually for each of the instruments in use, it was more convenient to select a particular instrument (No. 1), and to obtain comparison curves whereby any reading on any other instrument could be converted to the corresponding reading of No. 1. It was then necessary to calibrate only No. 1 in standard units, but in practice it was preferred to make the necessary exposures simultaneously on two or three instruments, all of whose readings were afterwards converted to the scale of No. 1.

Observation of the standard natural u.v. unit. Because of bad weather, among other reasons, there were only seven occasions on which the standard unit was observed at Leicester. For practical reasons the exposure used was three minutes with the sun at altitude 45° in a blue sky. The results are given in the following table.

Reading of No. 1 *Ultra-violet Daylight Integrator corresponding to* 3 *Standard Natural U.V. Minutes.*

Date	Mean Reading	Number of Instruments	Condition of sky
20.7.38	13	3	Cloudless; moderate haze.
3.8.38	15	2	A little cirrus; moderate haze.
23.8.38	19?	2	1/10 covered cumulus; some near sun.
25.7.39	17	2	Very good.
16.8.39	20?	1	Considerable cumulus.
18.8.39	19	2	Slight cloud; moderate haze.
24.8.39	19	2	Some cirrus.

The mean of the above observations is 17 arbitrary units. The estimated standard deviation of this mean is 1·0 unit, which is equivalent to about 10% of intensity, using equation (3) below. The estimated reading of No. 1 instrument, for three minutes' exposure to the sun and blue sky, when the sun is at altitude 45°, is therefore 17 units, with a standard deviation of 1 unit.

Wedge Constant. The optical wedges used in the daylight integrators are linear, at any rate for parallel beams of white light. If they may be assumed to be linear for diffuse ultra-violet radiation, such as they encounter in the daylight integrators, the following statement is true:

if x is a reading in the arbitrary units of instrument No. 1,
I standard natural u.v. minutes are equivalent to x, and
3 standard natural u.v. minutes are equivalent to 17 arbitrary units, then

$$\log_{10} \frac{\mathrm{I}}{3} = k(x - 17) \quad \ldots\ldots \quad (1)$$

where k is a property of the optical wedge, known as the *wedge constant.*

The base 10 will be used in this report for logarithms connected with k, although the natural base e is sometimes used. The equation can be rewritten

$$\mathrm{I} = 3 \times 10^{k(x-17)} \text{ standard natural u.v. minutes,}$$

or, for convenience in computation,

$$\mathrm{I} = 3 \times \operatorname{antilog}_{10} k(x - 17) \text{ standard natural u.v. minutes} \ldots\ldots \quad (2)$$

The above equations, which are merely modified forms of the definition of k, indicate the way to determine k. To do this it is not necessary for the sun to be at 45° altitude, but it is preferable for the sun to be high, and not changing altitude rapidly. Determinations of k may therefore be made on cloudless summer days, at solar noon. In practice it was found that on such days the sun and sky provided a sufficiently uniform source from 20 minutes before to 20 minutes after solar noon. If two exposures of different durations are made to this uniform source, if t_1 and t_2 are the times for the two exposures, and x_1 and x_2 the readings, then the two sets of values may be substituted in equation (1), and the difference between the resulting two equations gives

$$\log_{10} \frac{t_1}{t_2} = k(x_1 - x_2),$$

provided that reciprocity of time and intensity holds for the photographic paper. Now t_1, t_2, x_1, x_2, can all be measured. Hence a value can be found of the wedge constant k.

The determination of the wedge constant of instrument No. 1 is not yet quite satisfactory, because of shortage of observations. So far, five estimates of k have been made, and the mean of these estimates is

$$k = 0{\cdot}043, \text{ with an estimated standard deviation of } 0{\cdot}003.$$

Besides making more determinations of k, it is necessary to find out whether it was correct to assume that the wedges are linear under their conditions of use in the ultra-violet daylight integrators. There is also the possibility that the composition of the light received, within the waveband 3150Å to 3350Å, may vary sufficiently with varying height of sun to cause k to vary. Until these matters have been investigated, k will be taken provisionally as 0·043. Equation (2) can now be written,

$$\mathrm{I} = 3 \times 10^{0{\cdot}043(x-17)}$$

or $\mathrm{I} = 10^{0{\cdot}043(x-6)}$ approximately,

or $\mathrm{I} = \operatorname{antilog}_{10} 0{\cdot}043(x - 6)$ standard natural u.v. minutes .... (3)

Equation (3) provides a simple way of converting an observation to standard units from the arbitrary units of instrument No. 1.

2·722 *Casual errors* of the ultra-violet daylight integrator were estimated from a large number of observations by two or more instruments exposed simultaneously at the same place. The standard deviation of one observation varied from 0·9 to 2·1 arbitrary units, according to the particular instrument used.

The average estimate was 1·27 arbitrary units. From equation (3) in Section 2·721 it can be deduced that this corresponds to a difference in intensity of about 13%. There was no indication that the daylight integrators were more accurate in either strong or weak light, and this would not be expected since the instruments have a logarithmic scale. The standard deviation of a single observation of intensity, therefore, is about 13%, over a wide range of intensities. This satisfies condition (5) of Section 2·7.

2·723 *Variability with time* of the ultra-violet daylight integrator. The method of photographic photometry described in Section 2·71 is cheap and speedy, but it is rather liable to go wrong. The chief difficulty is its inadequate provision to ensure that results on a given date are comparable with results on any other date, say a year later. It has been found that the comparison curves between two instruments may change in a year, showing that the optical wedge or the silver filter of any instruments may change its optical properties. If every instrument could be readily tested with a standard ultra-violet source, this difficulty could be avoided completely, but the sun as a standard source is difficult to observe, and suitable sub-standards are not available. In Leicester the difficulty of variability of the instruments was only partially avoided, by comparing each instrument with instrument No. 1 each summer. Only two of the comparison curves were not appreciably different in the two summers, and two were changed by more than 1 to 2 arbitrary units. The result was that a number of observations had to be discarded. This difficulty may possibly be reduced by taking greater care in preparing the silver filters, and by further safeguarding them against the action of air and moisture.

Another difficulty of daylight integrators is that it is impossible to obtain commercial gaslight printing paper of constant sensitivity. A single batch of commercial paper is satisfactory, but two batches which were made at different times to the same specifications may give different readings with the daylight integrators by as much as six arbitrary units, or 80%. At Leicester this difficulty was avoided by choosing the type of paper with care, and by comparing each batch with the previous batch. A still better way would be to expose each disc of paper to a standard lamp, but this refinement was not used in Leicester. It would not have been safe to buy a large stock of papers, sufficient to last the whole survey, without making very special arrangements for storing it. Photographic paper is liable to deteriorate with time, and the same stock was therefore not used for more than six months.

It is clear that the instrument needs to be investigated further, and possibly re-designed, before it can be used as part of the routine equipment for investigating atmospheric pollution.

3·0 VARIATION OF POLLUTION WITH POSITION

3·1 Introduction

The main purpose of the Leicester Survey was to get a clear idea of the distribution of pollution in and around a normal city. In the first place a suitable city had to be chosen for the survey, and Leicester appeared to be very suitable from all points of view. It is the right size, for its population is 260,000 and its diameter as a source of smoke is from 3 to 6 miles; it was felt that the necessary observation posts in a town of this size could be kept going by a staff of three. Its shape is satisfactory; the ideal town for experiment would be in the form of a circle, and Leicester is more or less circular, although lengthening has taken place in both directions along the valley of the River Soar, which runs roughly from SSW to NNE. The factory chimneys are almost all within a mile of the city centre, and the residential areas, though differing in character, are fairly well distributed round and in the industrial area. Leicester lies in a hollow surrounded by low hills; as its lowest and highest points are 170 and 360 ft. respectively above sea level, it is probably not subject to anomalous winds and circulation. Finally, for a city of its size in Great Britain, Leicester is unusually well isolated from other large cities, so that not too much of the pollution in Leicester will have been brought there from outside. Fig. 3·1a shows how the position of Leicester is related to other industrial districts of England; Fig. 3·1b shows the general disposition of Leicester itself.

3·2 Observations

It was decided that the most convenient instruments for measuring pollution would be those where a continuous sample of air is taken, and the sample measured every 24 hours. Of the standard apparatus recommended by the Atmospheric Pollution Research Committee, the volumetric sulphur dioxide apparatus with smoke filter attachment is of this type. It is described in Sections 2·3 and 2·5. Another standard instrument needing attention once daily is the Automatic Filter (Section 2·4), which takes samples of air about every hour, and which gives hourly mean concentrations of black suspended impurity. Lastly among the daily changing instruments is the daylight integrator (Section 2·7), which was devised especially for use in this survey, and which measures the total ultra-violet daylight received by it from all directions in one day.

These three instruments were used extensively in the survey, and in addition two instruments of the monthly type were used. These were the standard Deposit Gauge and the standard Lead Peroxide Apparatus. They are described in Sections 2·2 and 2·6.

3·3 Stations

It was not easy to decide beforehand at what points in Leicester to take observations, but the previous experience gained by the Leicester Health Department, working as a Co-operating Body in the investigation of atmospheric pollution, was a valuable guide. The choice was very much narrowed by the number of places, such as premises of the Health Department and other Corporation departments, where facilities could be obtained for setting up apparatus. In view of the smallness of the staff to be employed on the survey, the number of sites was limited to 12: one in the centre of the city, three on the out-

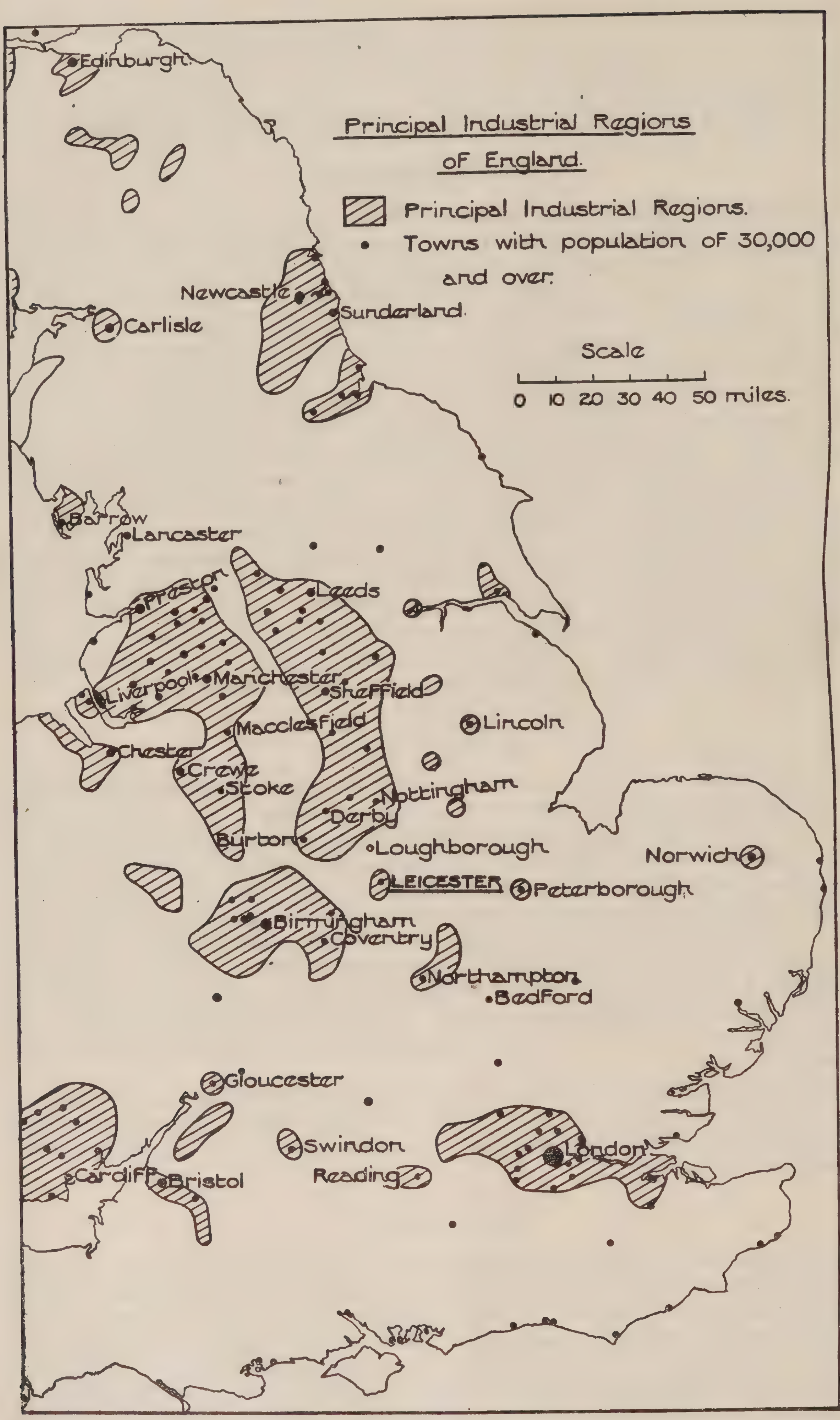

Principal Industrial Regions
of England.
Principal Industrial Regions.
Towns with population of 30,000 and over.
Scale
0 10 20 30 40 50 miles.
Edinburgh
Newcastle
Sunderland
Carlisle
Barrow
Lancaster
Preston
Leeds
Liverpool
Manchester
Sheffield
Lincoln
Macclesfield
Chester
Crewe
Stoke
Nottingham
Derby
Burton
Loughborough
Norwich
LEICESTER
Peterborough
Birmingham
Coventry
Northampton
Bedford
Gloucester
Swindon
Reading
London
Cardiff
Bristol

FIG. 3·1(a).

skirts of the industrial area, six in the suburbs, and two in the country so placed that, whatever the wind direction, one or both of them would be receiving as clean air as possible. Table 3·3 and the map (Fig. 3·1b) show the arrangement of stations which were finally chosen. Stations 13, 14, and 15 were not part of the original survey, but were introduced in April, 1939. In March, 1939, the

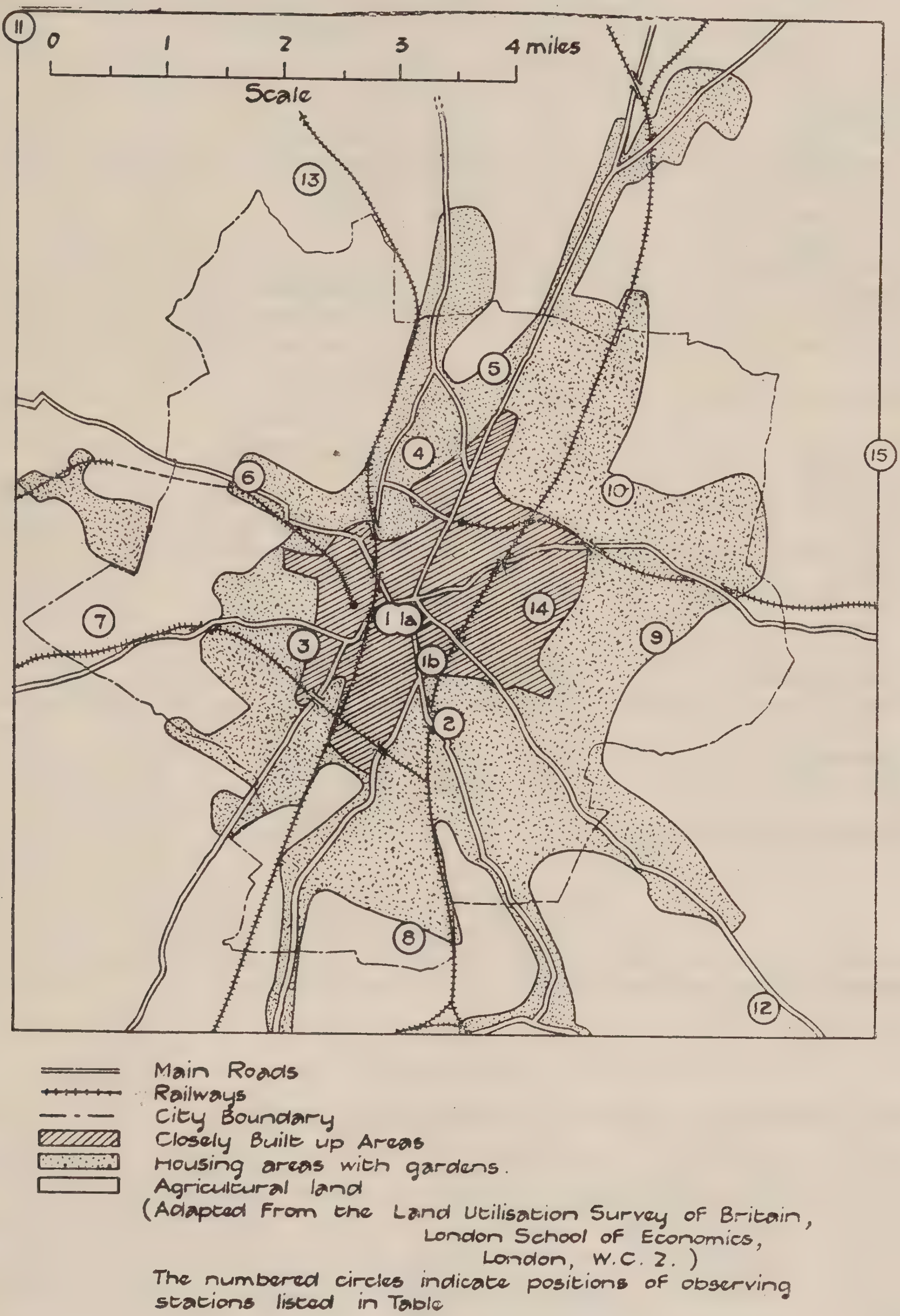


Fig. 3·1(b) Map of Leicester.

Committee decided that there was sufficient general evidence about the distribution of pollution, but that additional observations for one year could be usefully directed at certain specific problems. A scheme was prepared, in accordance with which stations 5, 6, 7, 8, 10, 11, and 12 closed down, and stations 13, 14, and 15 were introduced.

TABLE 3·3 *Observing Stations of the Leicester Survey*
Jan. 1937 - Dec. 1939

No.	Name	Bearing from centre of Leicester		Height above M.S.L.	Description of Surrounding District and number of Families per Acre		Routine Apparatus
		Miles		Feet			
1	Greyfriars	$\frac{1}{8}$	SW	200	Commercial	15	A, L, VS.
1a	Town Hall	$\frac{1}{8}$	S	200	Commercial	15	D, L, U.
1b	Regent Road	$\frac{1}{2}$	S	200	Residential	11	V (hourly).
2	University College	$1\frac{1}{4}$	SSE	290	Residential	6	A, L, VS, U.
3	Westcotes Maternity Home	1	WSW	220	Residential	11	A, D, L, VS, U.
4	Abbey Pumping Station	$1\frac{1}{4}$	N	180	Industrial, Poor Residential	8	A, L, VS, U.
5*	Belgrave Pumping Station	$2\frac{1}{4}$	NNE	170	Residential, Industrial, Open Country	4	L, VS, U.
6*	Isolation Hospital	$1\frac{3}{4}$	NW	250	Open Country, Residential	2	L, VS, U.
7*	Municipal Aerodrome	$2\frac{3}{4}$	W	310	Open Country	1	D, L, VS, U.
8*	Saffron Hill Cemetery	3	S	300	Open Country, Residential	3	L, VS, U.
9	City General Hospital	$2\frac{1}{4}$	E	320	Open Country, Residential	2	L, VS, U.
10*	City Mental Hospital	2	ENE	230	Open Country, Industrial, Residential	7	D, L, VS.
11*	Roecliffe Manor	6	NW	420	Wooded Country	<1	L, VS.
12*	Glen Gorse Golf Club	$4\frac{3}{4}$	SE	400	Open Country	<1	L, VS, U.
13†	Thurcaston	4	NNW	250	Open Country	<1	VS.
14†	Spinney Hill Park	1	E	280	Residential, Industrial	18	VS.
15†	Scraptoft Golf Club	$4\frac{1}{4}$	ENE	350	Open Country	<1	VS.

* Observations ceased March 1939.
† Observations began April 1939.

Abbreviations: A = automatic filter; D = deposit gauge; L = lead peroxide; VS = volumetric sulphur dioxide, with smoke filter; U = ultra-violet daylight.

3·4 Results

3·41 *Mean Distribution of Smoke and Sulphur Dioxide*

Table 3·41 gives the mean observation at each station during the summers of 1937 and 1938, and during the winters of 1937 (January-March only), 1937-8 and 1938-9, for three types of observation. The means are for all days, including Sundays and public holidays. The convention adopted throughout this report is to call the months of May-September "summer" and November-March "winter"; the reason for doing this is explained in Section 4·212.

In the two summers in Table 3·41 the pollution was nearly equal, but the winter of 1938-9 was quite definitely cleaner than the winter of 1937-8. This improvement can be completely explained, however, by reference to the differences of weather conditions of the two winters (see Table 6·4).

A better idea of the distribution of pollution near Leicester can be got from Figs. 3·41 a to f. For each type of observation, the means of the two successive summers have been plotted on a map. The same has been done for the two successive winters, ignoring results for January-March, 1937. Contour lines of equal pollution are drawn on each map to assist in visualizing the

distribution over an area. There is of course not nearly enough evidence to show that each contour is an ellipse. If circles are drawn instead of ellipses, it is found that each circle encloses too many stations to the east and west and too few to the north and south. Whatever their detailed form, the contours must be elongated towards the north and south, just as the industrial and residential parts of Leicester are elongated. It is also clear from the figures that Leicester has developed more towards the east than the west, causing a west-to-east asymmetry in the suburban observations. In some maps the outer contours might justifiably be allowed to bulge towards the east, but similar

TABLE 3·41 *Summer-Mean and Winter-Mean Distribution of Smoke and Sulphur Dioxide*

"Summer" refers to the five months May to September, and "winter" to the five months November to March. Figures in brackets are means of less than five months.

In the section concerned with the lead peroxide method, pairs of figures are given as for station 1. The first of each pair refers to station 1, the second to station 1a.

Station	1	2	3	4	5	6	7	8	9	10	11	12
Smoke : Milligrams per 100 cubic metres												
Summer 1937 ..	16	(13)	12	12	10	6	5	8	6	8	5	6
Summer 1938 ..	18	(12)	11	12	11	5	5	7	6	8	5	5
Jan. Feb. Mar. 1937	(38)	(20)	(25)	(18)	(16)	(10)	—	(10)	(9)	—	(10)	(5)
Winter 1937-8 ..	46	33	36	29	27	16	14	22	16	26	10	12
Winter 1938-9 ..	38	26	27	24	22	10	10	12	11	17	6	9
Sulphur Dioxide : concentration by volumetric method in volumes per 100 million												
Summer 1937 ..	5·5	3·5	2·0	2·5	2·0	1·5	2·0	1·5	2·0	2·5	—	1·0
Summer 1938 ..	6·0	2·0	2·0	2·5	2·0	1·5	1·5	2·0	1·5	2·5	1·0	1·0
Jan. Feb. Mar. 1937	(11·0)	(4·0)	(4·5)	(5·0)	(3·0)	(2·0)	—	(1·0)	(2·5)	—	(2·0)	(0·5)
Winter 1937-8 ..	15·0	6·5	5·5	5·5	4·0	3·0	2·0	4·0	3·0	5·5	2·5	2·0
Winter 1938-9 ..	12·5	5·5	4·5	6·0	3·5	1·5	2·0	2·0	2·0	4·5	1·5	1·0
Sulphur Dioxide : absorption by lead peroxide, as mg.SO_3/day/100 cm²												
Summer 1937 ..	1·5 2·0	1·1	0·7	1·0	0·6	0·7	0·6	0·5	0·7	0·6	0·7	0·4
Summer 1938 ..	1·6 1·7	0·9	0·6	1·0	0·6	0·7	0·6	0·5	0·7	0·6	0·6	0·4
Jan. Feb. Mar. 1937	(3·8) (4·2)	(2·4)	(2·2)	(2·6)	(1·6)	(1·5)	(1·1)	(1·0)	(1·4)	(1·8)	(1·0)	—
Winter 1937-8 ..	(4·0) (4·6)	2·5	2·0	2·2	1·7	1·5	1·3	1·1	1·7	1·7	1·2	1·1
Winter 1938-9 ..	3·7 4·4	2·0	1·8	2·4	1·6	1·3	1·2	0·8	1·6	1·6	1·0	0·7

ellipses have been drawn, partly for the sake of uniformity and partly because of insufficient data. The west-to-east asymmetry is most marked in the distribution of sulphur dioxide measured by the volumetric method, but this is not confirmed by the lead peroxide method. It is possible that there was a local source of sulphur dioxide near the volumetric apparatus at station 10, for the lead peroxide apparatus, being about 200 yards away, would not have been affected.

The difference in distribution between smoke and sulphur dioxide is apparent in Figs. 3·41. While the mean smoke concentration in the outer suburbs is between 0·3 and 0·4 of the smoke at the centre of Leicester, the corresponding

figures for sulphur dioxide are 0·15 to 0·33. The distribution of sulphur dioxide is thus more peaked than that of smoke. The reason for this is likely to be that the industries and central-heating plants in central Leicester produce a lower proportion of smoke to sulphur dioxide than the houses in the suburbs. There is a detailed discussion of this question in Section 3·5.

The effect of wind on distribution of pollution is not very plain in Figs. 3·41 because they are means of long periods of observations. In Section 3·49 it is shown that in a steady wind the contour lines of equal pollution are moved no more than $1\frac{1}{2}$ miles downwind. This is not a great distance, and when results for all wind directions are grouped into a single average it is not surprising that the effect of wind direction is obscured, in spite of the preponderance of westerly over easterly winds.

The seasonal variation of the distribution of pollution, if it is large enough, should be evident in Figs. 3·41. If the station readings in Fig. 3·41a are all multiplied by 2·4, they give a close approximation to the station readings in Fig. 3·41b. Hence the difference between summer and winter concentrations

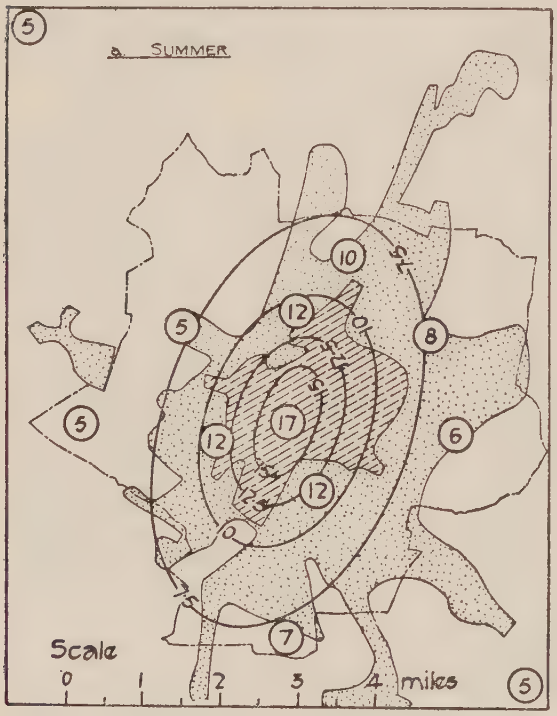


Fig. 3·41(a)

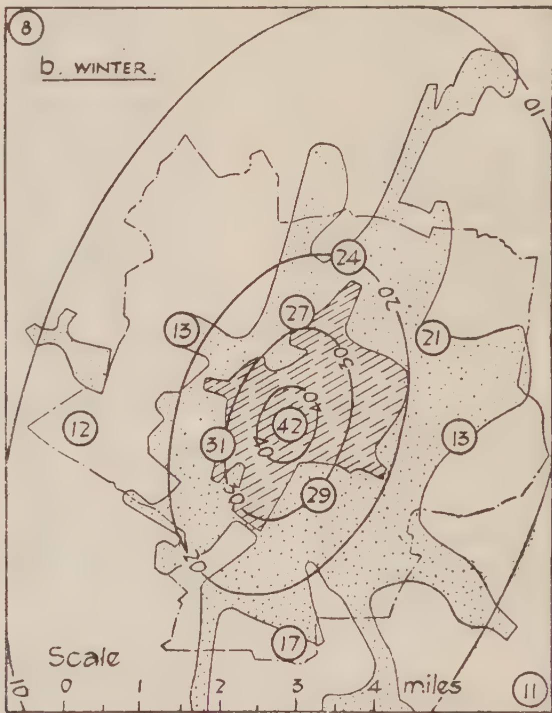


Fig. 3·41(b)

Mean Distribution of Smoke.
Concentration in mg. /100 cu.m.

of smoke in Leicester is one of magnitude. There is little difference in smoke distribution. The same is true with Figs. 3·41e and f for distribution of sulphur dioxide by the lead peroxide method, using the same factor of 2·4. Figs. 3·41 c and d, for the volumetric method, do not conform quite so well to the same rule. The departures could conceivably be explained by supposing that in winter there is a uniform concentration of about one part of ammonia per 100 million parts of air, and that all this ammonia is in the alkaline state.

3·411 *Mean Distribution on Sundays.* Figs. 3·411 a to d represent the mean distribution of pollution on Sundays; observations with the lead peroxide method were naturally not available. Public holidays have been counted as Sundays, and the same division into summer and winter has been used. Since they represent means of fewer observations, Figs. 3·411 a to d are less accurate than Figs. 3·41 a to d, but the two sets of figures indicate the differences between distribution on Sundays and weekdays. It is necessary, however, to allow for the contribution of Sundays and public holidays to Figs. 3·41.

A comparison of the two sets of figures reveals that the mean pollution on Sundays is everywhere lower than on all-days, and therefore is still lower than on weekdays. In fact pollution is lower by 20% to 50% on Sundays than on

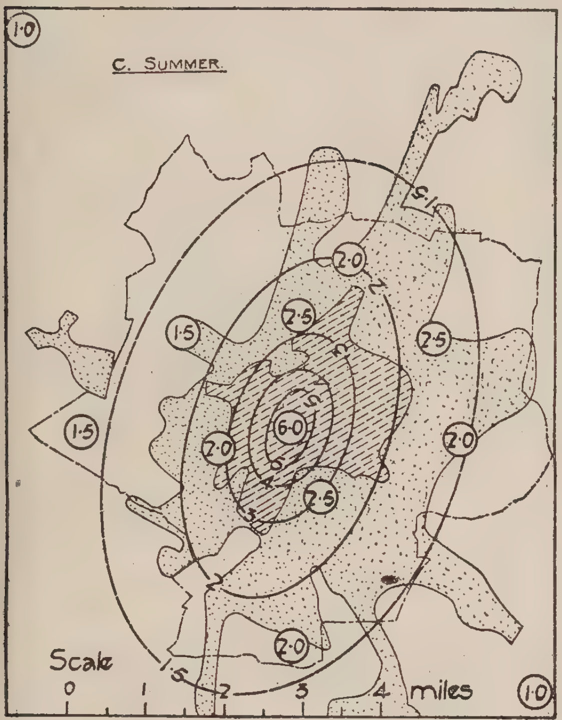


FIG. 3·41(c)

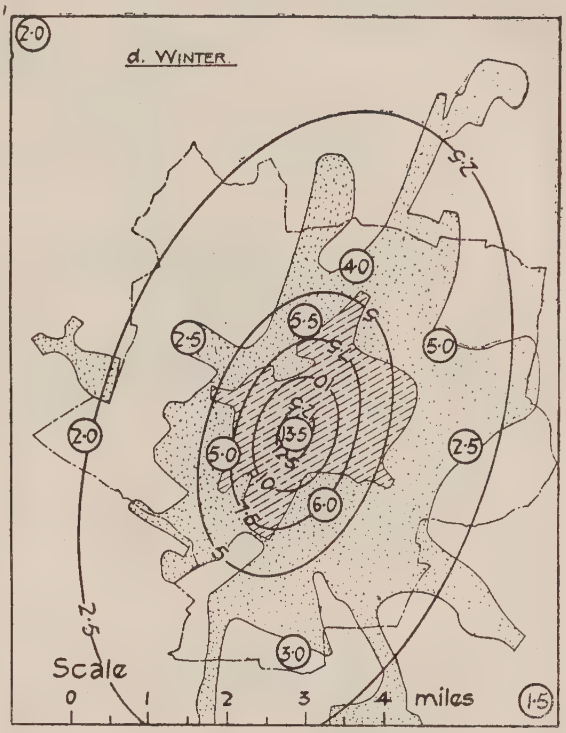


FIG. 3·41(d)

Volumetric Method.

Concentration in parts per 100 million.

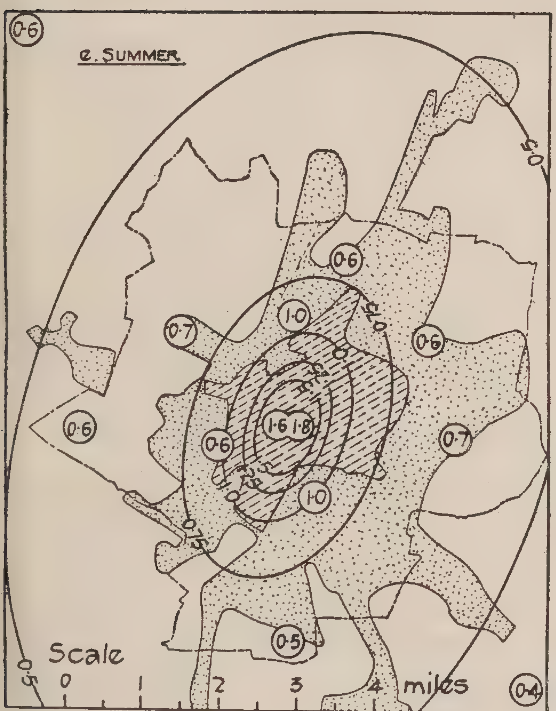


FIG. 3·41(e)

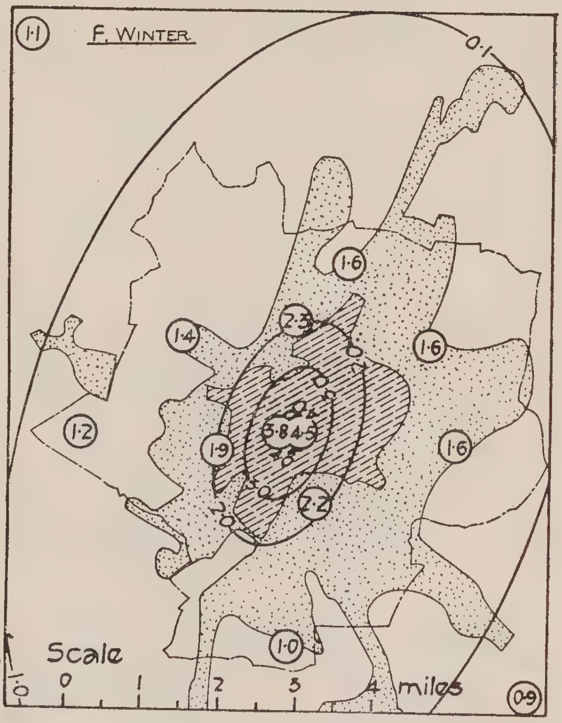


FIG. 3·41(f)

Lead Peroxide Method.

Rate of Sulphation as mg. SO_3/day/100 cm.^{2}

MEAN DISTRIBUTION OF SULPHUR DIOXIDE.

weekdays. The relative distribution of smoke is more uniform on Sundays than on all-days, and this can be seen by considering whereabouts in each figure the pollution is half and one-third the pollution at the centre. This conclusion is very interesting because it points to a variation in the emission of smoke.

Although at week-ends sulphur dioxide is reduced in amount as much a smoke, it does not show nearly so large a change in relative distribution. Thi will be discussed in Section 3·5, which deals with the emission of pollution.

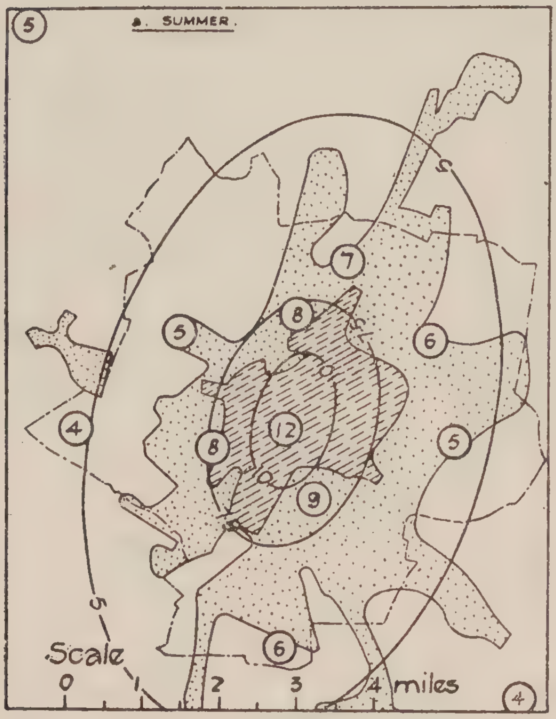


Fig. 3·411(a)

Fig. 3·411(b)

Sunday Mean Distribution of Smoke.

Concentration in mg. /100 cu.m.

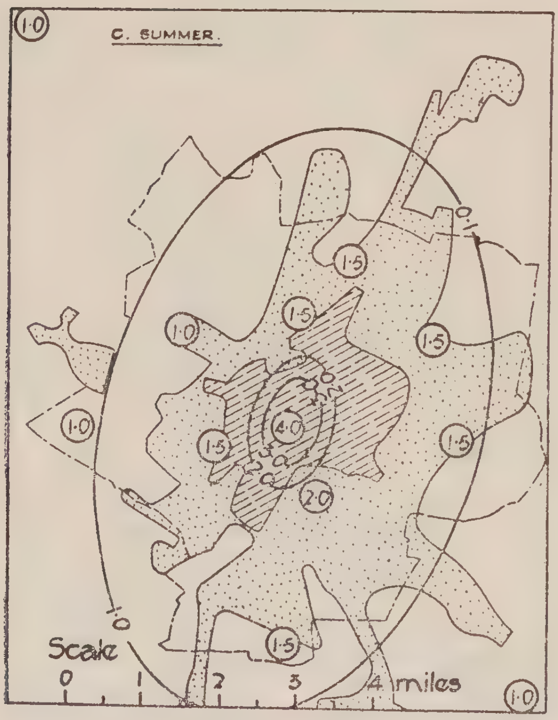


Fig. 3·411(c)

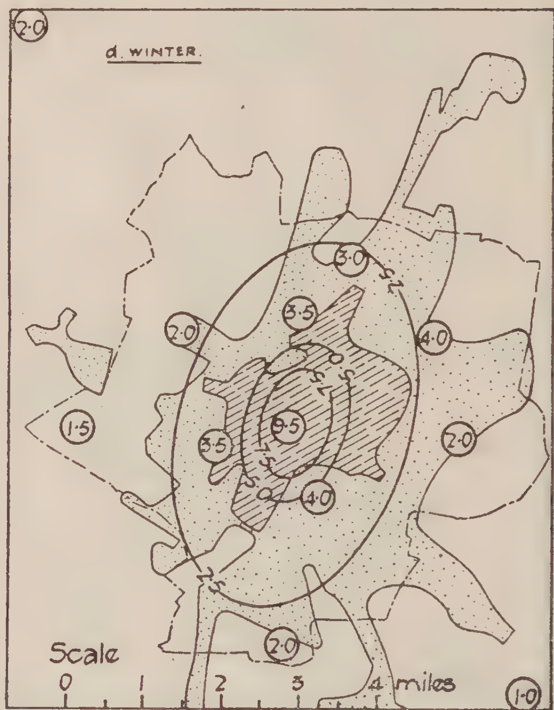


Fig. 3·411(d)

Sunday Mean Distribution of Sulphur Dioxide.

Volumetric method.

Concentration in parts per 100 million.

3·42 *Mean Distribution of Ultra-violet Daylight*

The method of presenting results for ultra-violet daylight is the same as for pollution. Figs. 3·42 represent the mean distribution of daylight in winter, or all-days and on Sundays. All instruments were placed in very open sites, and

corrections were applied for any obstructions which remained above the horizon. The reduction of daylight caused by crowded buildings or trees is therefore not recorded in Figs. 3·42. Isometric lines are again drawn as symmetrical ellipses, but it should be noted that if relief maps were made from Figs. 3·42 there would be a hollow over Central Leicester instead of a hump. The units in Figs. 3·42 are the standard natural minutes which were discussed in Section 2·721. It can be calculated that the winter daily mean ultra-violet daylight in Central Leicester is thus equivalent to about 20 minutes of sunshine in a blue sky with the sun 45° above the horizon, as compared with 25 to 26 minutes in the nearby country.

The reduction of daylight in the centre of Leicester is evidently due to solid matter suspended in the town air; it could not be due to additional atmospheric obscurity in the form of water condensates, because the air of towns is slightly warmer, and therefore slightly less humid than country air. The suspended solid matter which reduces ultra-violet radiation in towns may approximately be identified with smoke, as measured by the smoke filter. As would be

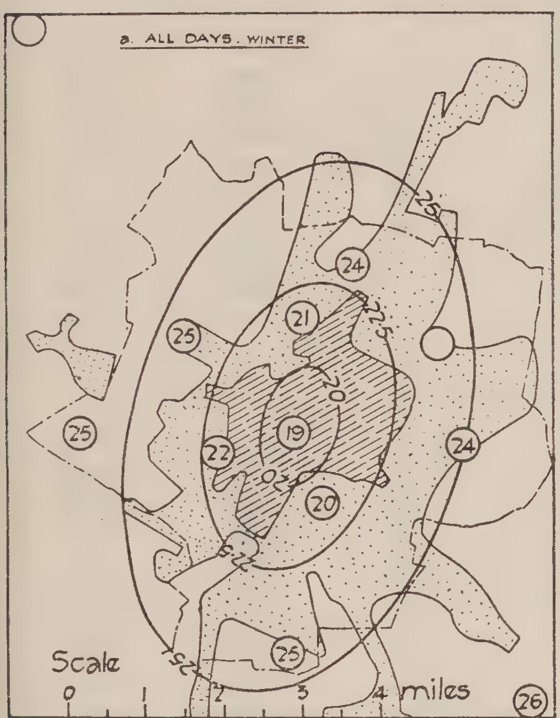


Fig. 3·42(a)

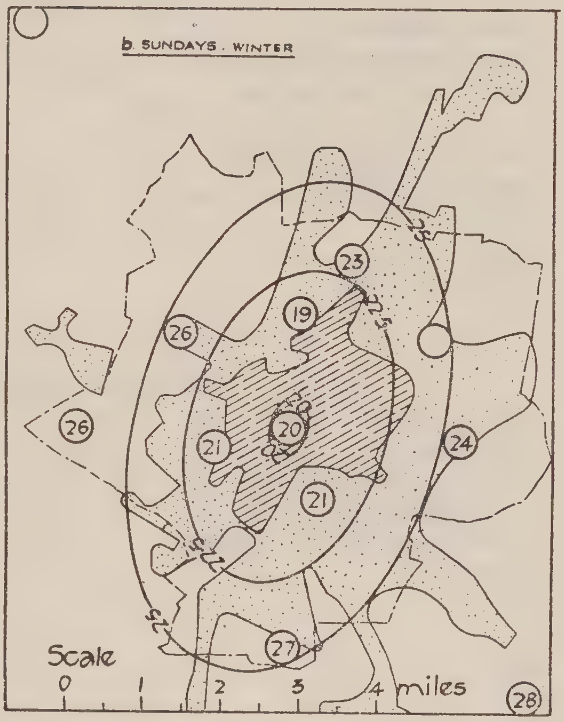


Fig. 3·42(b)

Mean Distribution of Ultra-violet Daylight.

Numbers are standard natural u.v. minutes per day. (See Section 2·721.)

expected, the descent to minimum daylight in the centre of Leicester is gradual, and not at all similar, for instance, to the sharp central peak in the distribution of sulphur dioxide.

On Sundays, slightly more ultra-violet daylight was received on an average (Fig. 3·42b). The minimum in the centre of Leicester was rather less pronounced.

In summer it was found that the losses of ultra-violet radiation in Leicester were more difficult to detect, and a contour map similar to Fig. 3·3a could not be drawn. The actual summer means were, in standard natural u.v. minutes per day: station 1a, 93; station 2, 98; station 3, 97; station 4, 90; station 5, 97; station 6, 88; station 7, 95; station 8, 103; station 9, 102; station 12, doubtful. The mean for stations 1a, 2, 3 and 4 was 94, and for stations 5, 6, 7, 8 and 9 it was 97 minutes per day. The average loss of ultra-violet daylight in central Leicester in summer months is therefore estimated as about 3%, but the standard error of this estimate is also about 3%. Hence it is not significantly established that there is any loss.

3·43 *Mean Distribution of Deposited Matter*

It would not have been possible in the three years of the Leicester Survey to include a thorough survey of deposited matter, for this would require probably five years' full-time work from two analytical chemists. Instead of dispensing with the deposit gauge entirely, however, it was arranged to take observations with four deposit gauges for the two years April, 1937, to March, 1939. The gauges were placed across Leicester, roughly from west to east, at stations 7, 3, 1a, and 10. Gauges had previously been maintained at stations 1a and 10 by the Leicester Health Department.

TABLE 3·43 *Summary of Deposit Gauge Results, April, 1937, to March, 1939*

Tonnes per sq. km. per month, except *p*H.

Station	1a	3	10	7
Distance from centre (miles)	0	1	1¾	2¾
SUMMER MEANS, MAY TO SEPTEMBER				
Total solids	7·89	5·56	4·79	3·00
Total undissolved matter	5·57	2·90	2·84	1·66
Total dissolved matter	2·32	2·66	1·90	1·34
Tar (soluble in CS_2)	0·11	0·08	0·06	0·04
Other combustible matter	1·49	0·90	1·13	0·43
Insoluble ash	3·99	1·92	1·65	1·18
SO_4''	0·96	0·83	0·66	0·42
Cl'	0·21	0·24	0·12	0·09
NH_4^+	0·10	0·08	0·06	0·05
*p*H	7·4	7·3	7·4	7·3
WINTER MEANS, NOVEMBER TO MARCH				
Total solids	9·70	4·77	3·81	2·04
Total undissolved matter	6·69	2·56	2·06	0·80
Total dissolved matter	2·51	2·22	1·71	1·25
Tar (soluble in CS_2)	0·12	0·06	0·06	0·03
Other combustible matter	1·31	0·69	0·63	0·27
Insoluble ash	5·25	1·83	1·69	0·50
SO_4''	1·33	0·73	0·74	0·50
Cl'	0·46	0·29	0·19	0·17
NH_4^+	0·10	0·07	0·06	0·04
*p*H	6·8	6·8	7·0	6·9

The results are presented in table 3·43, in the form of summer and winter means. It should be noted that the figures given for *p*H are geometric means. Fig. 3·43 depicts the same data, except for *p*H and total solids, in such a way as to show the variation of deposited matter with distance from the centre of Leicester. In this figure, deposits are expressed as percentages of deposit at station 1a, in the centre of Leicester. For comparison, curves are provided of the equivalent variation of suspended smoke and sulphur dioxide with distance from the centre of Leicester. The various components into which deposits are analysed appear to fall into two groups:

$$\left.\begin{array}{l}\text{total undissolved matter}\\ \text{undissolved ash}\\ \text{tar}\\ \text{other combustible matter}\end{array}\right\}\ \begin{array}{l}\text{which diminish with distance from the}\\ \text{centre of Leicester at a rate faster than,}\\ \text{or comparable with, suspended smoke}\\ \text{and sulphur dioxide}\end{array}$$

and

$$\left.\begin{array}{l}\text{total dissolved matter}\\ \text{dissolved } SO_4'' \text{ ion}\\ \text{dissolved } Cl' \text{ ion}\\ \text{dissolved } NH_4^+ \text{ ion}\end{array}\right\}\ \begin{array}{l}\text{which diminish with distance from the}\\ \text{centre of Leicester at a much slower}\\ \text{rate.}\end{array}$$

The first group is drawn with full lines in Fig. 3·43; this group contains undissolved matter in all the forms investigated. The second group, drawn

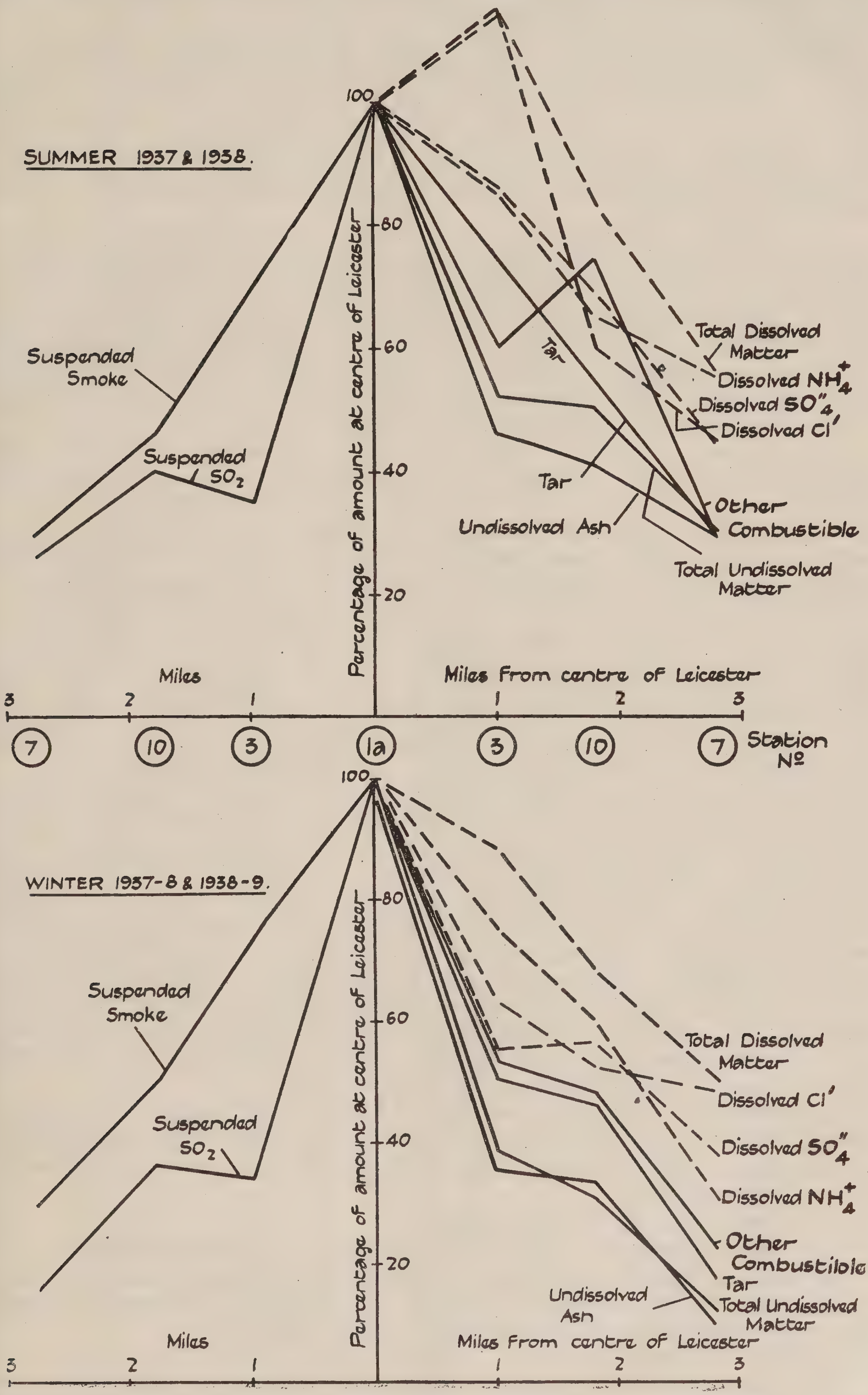


FIG. 3·43 VARIATION OF DEPOSITED MATTER ACROSS LEICESTER.

with broken lines, contains all forms of soluble matter. It is easy to understan the rapid decrease of the first group with distance from the centre of Leiceste: Much insoluble matter evidently falls quickly to ground within, say, half a mil of the chimney from which it is emitted.

The much slower decrease with distance of soluble matter shows that i remains suspended in the air a relatively long time before falling to earth. Thi must be because most of the soluble matter is emitted from chimneys in th gaseous form. Such gases as sulphur dioxide and ammonia are readily solubl in water droplets, and will be brought to earth by rain. This explanation i confirmed in Section 4·64, by the close connection between monthly rainfal and dissolved matter.

At first sight, it would be expected that the rate of deposition of sulphate would depend only on the rainfall and the concentration of sulphur dioxid near the ground. There must be additional influences at work, however, for as Fig. 3·43 shows, deposited sulphates are more evenly distributed thar suspended sulphur dioxide. One explanation is that the lateral distributior of sulphur dioxide is itself more even above chimney level than in the surfac layers. A second possible explanation is that there are considerable quantitie of dissolved impurity to be found in rain clouds.

It is at present difficult to test the second explanation, because it is no known whether there are drops of water in clouds which remain for long time in the liquid state. If they exist, such drops of water would have a bette chance of dissolving impurities from the air during their incessant motior within the cloud, than during their brief falling to earth, provided that there is impurity in the air at cloud level. In support of the first explanation, variou observers have found that the early part of a shower of rain contains most impurities. Also, some at least of the soluble matter must be either washed from the air by falling rain or deposited as a solid, for otherwise there would be no more dissolved matter at Station 1a than anywhere else. Table 3·43 makes it clear that there is about twice as much dissolved matter at Station 1a as at Station 7; hence at least 50% of the dissolved matter at Station 1a must be either washed from the air by falling rain or deposited as a solid.

Between stations 1a and 3 in Fig. 3·43 there is a very large reduction in undissolved ash. This reduction is much larger than that of suspended smoke, but it is similar to the reduction in concentration near the ground of sulphur dioxide gas. This is exactly what would be expected if undissolved ash and sulphur dioxide were both chiefly of industrial origin. Tar and other combustible matter, on the other hand, resemble smoke in their reduction with distance from the centre of Leicester. This supports the hypothesis that combustible matter is mainly of domestic origin and may be to some extent identified with smoke.

It is of interest that more chlorides are deposited in the centre of Leicester than in the suburbs and surrounding country. Deposited chlorides are evidently not all derived from sea spray, although in Section 4·222 a reason is given why some, at least, of the chlorides may be from the sea.

In conclusion, deposit gauge analyses at Leicester are too few to be a satisfactory survey of the distribution of deposits. But they clearly suggest that

(1) much of the dissolved matter is brought by rain, and may be present in the clouds;
(2) undissolved ash is chiefly industrial;
(3) the combustible portion of insoluble matter is chiefly domestic.

The first conclusion shows that an investigation of the pollution at cloud levels should be very profitable, and so too should an examination of the impurities of samples of water taken from clouds direct.

3·44 *Future Surveys*

Future surveys should be designed in the light of Figs. 3·41. Station 1, in the centre, is seen to have much more pollution than the nearby stations 2, 3 and

4. Confirmatory evidence is needed to support the high concentrations at Station 1, and this is forthcoming only in Figs. 3·41 e and f, where the concentrations of sulphur dioxide at Station 1a are even higher. In future surveys it would be better to have three or more fully equipped stations within ¼ mile of the centre of the town; then there would be no doubt at all about the representative character of observations at the most important point of the survey.

3·45 *Mean Wind Directional Tables*

From June 1st, 1937, onwards, continuous records of wind direction and velocity were taken, with a Dines pressure tube anemometer, at the Leicester

TABLE 3·45a *Distribution of Smoke: Summers* 1937, 1938.

The next four tables represent the bulk of two years' daily observations of smoke and sulphur dioxide at Leicester, worked up to demonstrate the distribution of pollution in different conditions of wind. All week-day observations, except public holidays, from May to September are included as "summer"; from November to March as "winter." The means for each station are expressed as percentage of the mean of the corresponding means for stations 1, 2, 3 and 4. Underneath each figure, after the symbol ±, is the estimate of its own standard deviation, so that the accuracy of each figure can be seen at once. The lowest figure is in **bold** type, the next lowest in *italic*; see Section 3·47.

Station ..	..	Days	1	2	3	4	5	6	7	8	9	10	11	12
CALMS		13	135 ±9	93 ±19	71 ±8	102 ±7	74 ±7	55 ±5	43 ±4	66 ±6	43 ±5	48 ±6	**38** ±6	*40* ±4
LIGHT WINDS 1 to 4 m.p.h.	N	10	116 ±8	94 ±5	82 ±10	100 ±7	82 ±6	52 ±6	**37** ±3	71 ±8	48 ±6	57 ±7	51 ±9	*48* ±7
	NE	6	139 ±9	80 —	106 ±11	66 ±13	54 ±15	36 ±5	*31* ±4	74 ±11	38 ±10	42 ±6	43 ±5	**29** ±4
	E	5	133 ±20	—	91 ±24	95 ±19	68 ±19	40 ±7	60 ±17	81 ±4	*33* ±5	44 ±8	51 ±12	**25** ±5
	SE	8	126 ±8	70 ±15	92 ±5	110 ±10	59 ±5	56 ±9	44 ±5	52 ±7	**29** ±4	49 ±8	38 ±8	*31* ±7
	S	12	129 ±6	88 ±6	88 ±9	106 ±11	118 ±11	60 ±11	39 ±6	50 ±4	41 ±3	65 ±7	**35** ±5	*37* ±5
	SW	20	139 ±7	90 ±10	79 ±6	97 ±5	86 ±7	44 ±4	*42* ±3	49 ±4	60 ±5	72 ±7	**39** ±3	*42* ±3
	W	9	130 ±6	117 ±14	83 ±8	95 ±9	98 ±13	**39** ±6	*46* ±5	58 ±6	66 ±10	85 ±9	48 ±6	68 ±10
	NW	7	131 ±12	100 —	85 ±9	96 ±5	97 ±11	45 ±3	*42* ±4	71 ±5	49 ±5	81 ±5	**36** ±4	49 ±6
MODERATE WINDS >4 m.p.h.	N	12	120 ±8	111 ±8	92 ±7	80 ±6	78 ±13	**37** ±3	46 ±6	78 ±7	*45* ±6	57 ±6	48 ±8	53 ±8
	NE	4	155 ±9	100 ±4	95 ±6	52 ±6	32 ±5	20 ±4	25 ±6	52 ±10	**12** ±3	*18* ±3	22 ±6	*18* ±5
	E	0	—	—	—	—	—	—	—	—	—	—	—	—
	SE	11	114 ±10	52 ±4	104 ±6	114 ±11	83 ±6	43 ±4	33 ±4	41 ±4	**23** ±3	42 ±5	30 ±4	*29* ±4
	S	27	143 ±5	73 ±5	87 ±5	92 ±5	92 ±6	41 ±3	*33* ±3	40 ±3	38 ±3	63 ±3	36 ±3	**27** ±3
	SW	38	171 ±7	82 ±6	73 ±4	83 ±3	77 ±7	*38* ±2	43 ±2	46 ±4	49 ±3	84 ±5	43 ±5	**36** ±4
	W	25	143 ±7	117 ±10	80 ±6	79 ±5	79 ±6	53 ±4	**44** ±3	61 ±5	71 ±6	84 ±7	57 ±5	*55* ±4
	NW	14	131 ±8	93 ±13	84 ±6	82 ±9	76 ±9	**45** ±5	56 ±7	55 ±8	59 ±6	83 ±7	*47* ±5	51 ±5

Health Department's climatological station at the City General Hospital (Station 9 on the map Fig. 3·16). These observations were always immediately available to the Atmospheric Pollution Survey. The result is that it has been possible to assign to most days a mean wind velocity and direction for Leicester. On about 10% of the days the wind was too variable for means to be assigned.

TABLE 3·45b *Distribution of Smoke: Winters* 1937-8, 1938-9.

Station ..	..	Days	1	2	3	4	5	6	7	8	9	10	11	12
CALMS		6	121 ±13	94 ±5	103 ±9	77 ±9	71 ±13	40 ±4	*32* ±7	57 ±9	33 ±14	54 ±8	**22** ±4	36 ±6
LIGHT WINDS 1 to 4 m.p.h.	N	8	113 ±11	96 ±10	108 ±13	89 ±7	56 ±5	56 ±7	36 ±8	86 ±10	**27** ±3	55 ±9	36 ±8	*28* ±4
	NE E SE	2 2 3	130 ±9	87 ±7	108 ±10	74 ±5	62 ±10	37 ±4	36 ±5	56 ±12	**21** ±4	56 ±9	*24* ±6	29 ±4
	S	8	112 ±11	80 ±10	112 ±7	98 ±6	80 ±11	42 ±3	31 ±4	38 ±7	44 ±6	69 ±11	**19** ±1	**19** ±2
	SW	6	119 ±13	92 ±11	100 ±9	86 ±5	86 ±16	55 ±10	52 ±9	58 ±8	72 ±13	90 ±16	**19** ±4	*43* ±7
	W	5	131 ±10	104 ±11	87 ±4	76 ±6	89 ±13	41 ±7	*39* ±7	63 ±4	41 ±10	89 ±13	**38** ±8	52 ±4
	NW	2	(168)	(82)	(78)	(72)	(88)	(*40*)	(**38**)	(45)	(50)	(110)	(45)	(45)
MODERATE WINDS 5 to 10 m.p.h.	N	16	119 ±4	114 ±7	98 ±6	66 ±6	55 ±6	*44* ±5	46 ±5	98 ±8	**43** ±7	47 ±6	*44* ±4	*44* ±5
	NE	4	140 ±5	82 ±8	111 ±12	58 ±10	46 ±17	22 ±6	29 ±3	55 ±15	**14** ±1	*17* ±7	45 ±19	20 ±5
	E	8	141 ±10	84 ±9	108 ±9	73 ±6	44 ±9	43 ±6	48 ±5	52 ±5	**23** ±3	29 ±4	29 ±7	*27* ±3
	SE	13	114 ±8	69 ±5	114 ±6	99 ±5	71 ±7	46 ±3	36 ±4	33 ±3	25 ±3	40 ±3	**19** ±5	*24* ±2
	S	16	131 ±10	70 ±4	100 ±7	92 ±6	109 ±8	35 ±4	27 ±2	35 ±3	31 ±3	58 ±5	**20** ±3	*24* ±2
	SW	31	142 ±5	83 ±3	85 ±3	87 ±4	93 ±5	34 ±2	38 ±4	40 ±3	39 ±2	89 ±5	**24** ±2	*30* ±2
	W	11	128 ±11	111 ±7	87 ±6	75 ±7	67 ±8	36 ±3	*35* ±2	48 ±5	70 ±7	88 ±10	**23** ±5	36 ±4
	NW	6	138 ±10	103 ±9	82 ±5	75 ±7	50 ±6	*41* ±5	46 ±6	58 ±8	84 ±11	88 ±11	(**20**)	58 ±9
FRESH WINDS >10 m.p.h.	N	10	130 ±10	117 ±12	89 ±5	59 ±6	32 ±8	*28* ±5	40 ±6	82 ±8	**24** ±4	39 ±7	41 ±8	38 ±6
	NE	7	138 ±8	98 ±5	100 ±8	59 ±9	28 ±3	21 ±3	22 ±3	64 ±8	**19** ±4	**19** ±3	27 ±9	22 ±3
	E	3	(157)	(63)	(107)	(73)	(15)	(45)	(35)	(35)	(*10*)	(20)	(**8**)	(22)
	SE	8	130 ±10	60 ±5	91 ±13	104 ±6	71 ±9	58 ±12	31 ±2	39 ±3	*24* ±3	38 ±4	**22** ±6	26 ±3
	S	14	148 ±8	65 ±5	88 ±6	98 ±6	83 ±6	32 ±3	*24* ±3	32 ±3	*24* ±2	55 ±5	28 ±4	**17** ±2
	SW	34	162 ±6	75 ±4	76 ±4	81 ±4	108 ±6	31 ±7	28 ±6	35 ±7	41 ±3	89 ±4	**21** ±2	*26* ±2
	W	16	159 ±6	99 ±5	78 ±5	65 ±3	52 ±5	**30** ±3	*32* ±2	45 ±4	75 ±7	89 ±9	34 ±6	45 ±3
	NW	6	124 ±13	124 ±6	92 ±13	63 ±7	52 ±9	36 ±8	*30* ±5	55 ±8	56 ±9	49 ±7	(**18**)	62 ±9

With the help of the Meteorological Office's Daily Weather Report, mean daily wind directions and velocities, though less accurate, were estimated for May 1937. About 640 days were then available, on which were known the mean wind direction and velocity, and the mean concentrations of smoke and sulphur dioxide at the 12 stations of the survey. (About 5% of the observations of pollution had been missed for such reasons as failure of apparatus and local building operations.) About 100 of these days were Sundays and public holidays, and were excluded; the entire months of April and October were also discarded temporarily. The remainder, about 460 days, were then sorted as follows:

(1) The months of May to September, 10 in all, were taken together, and called "summer."

(2) Summer days were grouped into days of calms, N, NE, E, SE, S, SW, W, and NW winds, and further into days of mean wind velocity 1 to 4 m.p.h., or greater than 4 m.p.h.: 17 groups in all.

TABLE 3·45c *Distribution of Sulphur Dioxide: Summers* 1937, 1938.

Station		Days	1	2	3	4	5	6	7	8	9	10	11	12
CALMS		13	165 ±10	92 ±10	53 ±10	67 ±7	55 ±8	48 ±6	48 ±4	66 ±7	53 ±6	58 ±12	**22** ±5	*28* ±6
LIGHT WINDS 1 to 4 m.p.h.	N	10	171 ±9	102 ±6	70 ±8	68 ±8	44 ±9	40 ±10	47 ±10	73 ±11	49 ±10	53 ±7	**26** ±8	*31* ±8
	NE	6	207 ±14	75 —	73 ±5	28 ±9	23 ±7	*22* ±8	38 ±9	55 ±14	40 ±8	56 ±10	28 ±3	**20** ±7
	E	5	164 ±10	—	72 ±10	65 ±19	34 ±9	34 ±13	45 ±12	55 ±14	*32* ±7	54 ±7	40 ±15	**24** ±8
	SE	8	142 ±15	50 ±9	87 ±11	91 ±8	50 ±5	51 ±6	44 ±9	50 ±5	48 ±8	63 ±9	**23** ±6	*29* ±4
	S	12	185 ±8	54 ±7	62 ±3	83 ±6	68 ±7	53 ±13	45 ±6	52 ±11	45 ±4	84 ±11	*35* ±6	**26** ±6
	SW	19	190 ±9	69 ±9	41 ±6	73 ±6	73 ±7	*33* ±4	43 ±4	46 ±6	65 ±7	89 ±13	43 ±8	**28** ±5
	W	9	184 ±10	93 ±9	65 ±5	63 ±7	58 ±9	51 ±5	58 ±5	78 ±10	78 ±10	116 ±16	*46* ±9	**45** ±9
	NW	7	199 ±9	80 ±6	51 ±7	54 ±6	52 ±6	37 ±6	51 ±8	74 ±10	59 ±9	81 ±9	**28** ±6	*34* ±6
MODERATE WINDS 4 m.p.h.	N	12	163 ±14	103 ±11	72 ±7	65 ±9	49 ±8	**30** ±5	46 ±7	96 ±10	40 ±9	95 ±15	36 ±8	*32* ±6
	NE	4	182 ±16	92 ±6	100 ±6	28 ±5	40 ±6	*12* ±3	25 ±9	52 ±10	**8** ±8	22 ±6	25 ±5	12 ±3
	E	0	—	—	—	—	—	—	—	—	—	—	—	—
	SE	11	131 ±10	34 ±7	100 ±8	123 ±11	55 ±11	54 ±6	45 ±9	35 ±5	35 ±7	61 ±7	**22** ±4	*24* ±5
	S	27	176 ±7	45 ±6	53 ±4	113 ±7	86 ±6	32 ±3	30 ±4	37 ±5	43 ±7	80 ±7	*28* ±3	**16** ±3
	SW	30	211 ±8	64 ±8	46 ±4	69 ±7	82 ±10	29 ±3	39 ±4	49 ±6	60 ±7	75 ±9	*28* ±3	**18** ±3
	W	24	181 ±8	114 ±11	43 ±6	53 ±5	46 ±6	36 ±5	40 ±4	41 ±5	62 ±6	102 ±8	*31* ±5	**30** ±6
	NW	12	195 ±10	78 ±11	55 ±7	51 ±4	51 ±6	57 ±13	*45* ±7	68 ±10	58 ±10	100 ±9	52 ±8	**38** ±8

(3) The months of November to March, 10 in all, were taken together, and called "winter."

(4) Winter days were grouped into calms and the same 8 wind directions, and further into days of mean wind velocity 1 to 4 m.p.h., 5 to 10 m.p.h., or greater than 10 m.p.h.: 25 groups in all.

TABLE 3·45d *Distribution of Sulphur Dioxide: Winters* 1937-8, 1938-9.

Station ..		..	1	2	3	4	5	6	7	8	9	10	11	12
		Days												
CALMS		6	167 ±7	90 ±6	83 ±8	60 ±4	33 ±10	43 ±4	*18* ±8	55 ±12	28 ±8	57 ±9	23 ±5	**13** ±4
LIGHT WINDS 1 to 4 m.p.h.	N	8	166 ±5	89 ±9	78 ±6	62 ±10	46 ±12	52 ±13	30 ±6	69 ±6	*22* ±4	54 ±11	28 ±5	**20** ±6
	NE E SE	2 2 3	178 ±8	65 ±9	82 ±6	65 ±11	38 ±3	27 ±4	30 ±3	34 ±10	23 ±5	31 ±8	*15* ±5	**14** ±4
	S	8	179 ±9	68 ±8	67 ±6	83 ±5	71 ±13	36 ±4	25 ±6	43 ±5	30 ±4	78 ±9	*16* ±4	**11** ±3
	SW	6	152 ±13	95 ±11	62 ±6	93 ±6	57 ±9	37 ±4	42 ±5	*29* ±7	47 ±4	91 ±9	30 ±10	**20** ±4
	W	5	158 ±5	118 ±6	66 ±4	59 ±3	47 ±10	48 ±10	37 ±7	51 ±5	57 ±14	89 ±12	**28** ±5	*30* ±4
	NW	2	(180)	(100)	(55)	(65)	(45)	(45)	(**10**)	(40)	(40)	(135)	(70)	(**10**)
MODERATE WINDS 5 to 10 m.p.h.	N	15	166 ±7	108 ±7	72 ±4	53 ±6	*25* ±6	34 ±7	29 ±4	91 ±11	28 ±5	48 ±6	36 ±6	**16** ±4
	NE	4	218 ±21	62 ±18	89 ±13	29 ±13	14 ±6	18 ±10	29 ±4	39 ±10	*6* ±4	12 ±3	22 ±13	**4** ±1
	E	8	177 ±10	84 ±5	77 ±8	61 ±12	27 ±6	39 ±10	41 ±4	39 ±7	*18* ±5	36 ±9	28 ±8	**17** ±7
	SE	13	164 ±7	48 ±3	87 ±5	97 ±7	51 ±7	44 ±4	31 ±7	26 ±6	18 ±6	40 ±5	*14* ±2	**12** ±4
	S	16	190 ±8	45 ±4	51 ±4	107 ±7	71 ±6	25 ±4	20 ±4	22 ±4	*19* ±4	64 ±5	19 ±3	**10** ±3
	SW	31	200 ±5	72 ±4	48 ±3	78 ±4	89 ±6	*18* ±3	20 ±2	25 ±3	31 ±3	102 ±7	21 ±2	**15** ±4
	W	11	182 ±10	105 ±7	54 ±5	57 ±9	39 ±7	30 ±3	32 ±5	30 ±6	47 ±5	99 ±7	*22* ±5	**19** ±4
	NW	6	152 ±15	118 ±15	62 ±3	69 ±12	*27* ±5	37 ±5	38 ±3	47 ±6	57 ±4	75 ±10	(**20**)	35 ±6
FRESH WINDS > 10 m.p.h.	N	10	174 ±9	116 ±8	67 ±9	37 ±5	**15** ±6	22 ±7	26 ±3	76 ±9	21 ±6	37 ±7	28 ±6	*19* ±6
	NE	7	202 ±9	69 ±7	103 ±6	24 ±8	16 ±6	12 ±4	*10* ±4	46 ±8	*10* ±0	25 ±5	32 ±4	**7** ±4
	E	3	(197)	(90)	(78)	(32)	(12)	(28)	(42)	(22)	(*8*)	(15)	(10)	(**5**)
	SE	8	151 ±16	62 ±10	82 ±11	108 ±13	55 ±9	51 ±12	35 ±7	27 ±6	*15* ±3	47 ±9	18 ±5	**14** ±5
	S	14	206 ±11	43 ±8	48 ±5	102 ±9	71 ±6	22 ±3	28 ±5	*19* ±4	24 ±3	56 ±6	21 ±4	**8** ±3
	SW	34	215 ±6	60 ±6	41 ±2	84 ±3	80 ±5	*20* ±2	23 ±2	22 ±3	24 ±3	94 ±7	22 ±2	**8** ±2
	W	14	209 ±11	90 ±8	42 ±5	58 ±6	32 ±6	23 ±4	*18* ±3	20 ±4	52 ±7	89 ±7	44 ±7	**15** ±5
	NW	6	156 ±11	129 ±18	54 ±8	51 ±7	*24* ±9	**19** ±3	*24* ±5	43 ±8	51 ±5	49 ±9	(38)	41 ±9

Rather more refined grouping was possible in winter for two reasons. Winter observations of pollution have a higher percentage accuracy, because pollution is higher; and also in winter there are many more days of high mean wind velocity greater than 10 m.p.h.

These 42 groups of days were then dealt with in the following way. The average of the smoke readings at the four most central stations (stations 1, 2, 3 and 4; Fig. 3·16) was found for each day, and called the "Central Leicester Average." The smoke reading for each of the 12 stations was then expressed as percentage of the Central Leicester Average for each day. The average was then found of the percentage readings of each station, for each of the 42 groups of days. Volumetric sulphur dioxide readings were treated in the same way. The final averages are tabulated in Tables 3·45 a to d.

The reason for the above rather complicated percentage treatment is important. It was found to be quite common for all stations to show on one day five or six times as much smoke and sulphur dioxide as on the next day (examples are given in Table 3·45e). These day-to-day variations are considered in Section 4·7, and are largely due to differences in turbulence. Such phenomena as turbulence influence all parts of Leicester proportionally, and must therefore be eliminated by the above percentage treatment. Annual variation

TABLE 3·45e *Examples of Day-to-Day Variation in Concentrations of Smoke and Sulphur Dioxide in Leicester*

Station	1	2	3	4	5	6	7	8	9	10	11	12
	SMOKE, milligrams per 100 cu. metres											
Mon. 15th Nov. '37	68	31	35	30	41	16	9	17	24	52	20	19
Tue. 16th	93	—	144	71	69	43	60	239	—	79	13	36
Wed. 17th	50	14	25	17	6	15	12	11	3	6	3	5
Thu. 18th	38	21	24	14	1	9	7	8	3	5	—	6
Fri. 19th	47	22	19	18	35	11	9	11	—	17	11	10
Sat. 20th	61	32	26	27	28	16	20	17	14	35	15	16
	SULPHUR DIOXIDE, volumes per 100 million											
Mon. 15th Nov. '37	12·0	8·0	3·5	5·0	3.5	3·5	0·0	2·0	—	10·5	5·0	1·5
Tue. 16th	33·0	24·5	25·5	11·0	3·0	7·0	0·5	11·5	—	7·5	1·5	2·0
Wed. 17th	25·0	9·0	8·5	4·5	3·0	5·5	3·0	3·5	1·5	2·0	1·0	1·5
Thu. 18th	16·5	6·0	7·5	2·5	0·5	2·5	2·0	2·0	1·5	0·5	—	0·0
Fri. 19th	15·5	5·0	4·0	3·0	1·0	2·0	1·5	2·0	—	3·5	3·5	0·0
Sat. 20th	14·0	6·5	4·0	4·5	2·5	3·0	1·5	4·0	3·0	8·5	5·0	0·0
	SMOKE, milligrams per 100 cu. metres											
Mon. 13th June '38	18	18	14	21	10	8	5	8	6	8	8	7
Tue. 14th	27	35	18	22	16	3	11	7	8	18	4	13
Wed. 15th	7	9	7	5	6	4	5	6	5	9	4	6
Thu. 16th	21	26	14	10	6	8	4	6	9	—	6	7
Fri. 17th	20	27	6	20	13	7	7	—	5	—	4	8
Sat. 18th	15	8	15	11	10	8	4	9	6	8	3	4
	SULPHUR DIOXIDE, volumes per 100 million											
Mon. 13th June '38	3·5	2·5	2·0	1·5	1·5	1·5	1·5	2·5	2·5	1·0	1·1	1·0
Tue. 14th	9·5	4·5	2·5	2·5	2·5	3·0	3·0	3·0	3·0	4·0	1·0	1·0
Wed. 15th	5·0	1·0	1·5	1·0	1·0	1·5	1·0	2·5	1·5	2·5	1·0	1·5
Thu. 16th	4·0	3·0	2·5	2·5	3·0	2·0	2·0	3·5	2·5	—	1·5	1·5
Fri. 17th	4·5	4·5	4·0	3·5	2·0	4·0	2·0	—	2·0	—	1·0	2·0
Sat. 18th	8·0	2·0	2·5	4·5	4·0	1·0	1·5	3·0	2·0	2·5	1·5	1·5

is eliminated at the same time, since it was shown in Section 3·41 that the pollution in different parts of the town undergoes nearly the same proportional annual variation.

One great advantage of taking the mean of numbers of independent observations is that an idea can also be got of the dependability of each observation and of the mean. The mathematical concept used for describing dependability is called the standard deviation. Any estimate will be wrong by more than its standard deviation less than one time in three (Section 6·12). In Tables 3·45 each mean is followed by its standard deviation, and so its order of accuracy is evident at once. It is seen that the different means all over the tables differ by much more than their standard deviations. Therefore 42 is a suitable number of groups in which to divide the 460 observations.

If the percentage treatment had not been employed the standard deviations would have been very much bigger, and the discussions of different aspects of the tables would have been less confident.

Tables 3·45 play the leading part in these considerations of the distribution of pollution.

3·46 *Distribution of Pollution in Calm Weather*

The first rows of Tables 3·45 give the mean distribution in calms, expressed as percentages of the average for Central Leicester. Although the standard deviations of these estimates are not unduly large compared with others in the same tables, the absolute concentrations of pollution during calm weather were very variable indeed; making allowance for yearly and weekly cycles, the daily smoke in calms varied from 0·5 to 5·0 times its normal concentration, and sulphur dioxide from 0·6 to 3·2 times its normal concentration. This great variability is due, partly at least, to variations in turbulence, and is discussed in Section 4·71. Its importance here is to render of little value any discussion of average pollution in calms. Instead, it is convenient to convert the percentages in tables 3·45 to arbitrary units suitable for comparison with figures 3·41. This has been done in figures 3·46, by making the mean for Central Leicester the same as in figures 3·41.

There are two ways in which figures 3·46 might be misleading. Firstly, calms with a wind of 0·0 m.p.h. never occur, particularly for 24 hours at a stretch. A calm was registered on days when the average wind velocity recorded by the Dines pressure tube anemometer was less than 0·75 m.p.h. Secondly, there tends to be little turbulence in calm weather, in winter especially, and this makes for high concentrations of pollution. Therefore the numerical values in figures 3·46 are smaller than are usually observed in calms. The values most likely to be observed can be estimated with the aid of the regression lines of Fig. 4·71b.

Figures 3·46 are therefore in units suitable for comparison with figures 3·41, but are not representative of the average pollution to be found in calms. Comparison of figures 3·46 with figures 3·41 shows that they are very similar; and that if the country concentrations in figures 3·41 were reduced by about 10%, results nearly indistinguishable from figures 3·46 would follow. (The west-to-east asymmetry already noted in certain mean distributions occurs also in calms.) Thus the distribution of pollution in calms is only slightly more centralized than the mean distribution. The explanation of this remarkable result seems to be the surprisingly small changes in distribution of pollution produced by any wind (see Section 3·49). The wind-frequencies in Leicester in the periods considered were markedly asymmetrical, westerly winds being from two to four times as common as easterly winds; yet the distributions in figures 3·41 are nearly symmetrical.

This empirical result has a practical advantage. In Section 3·5 it is shown that the distribution of sources of pollution may be estimated, if we know the distribution of pollution in calm weather. But long periods of calm are not at all common, and it might be necessary to wait several months for even a single

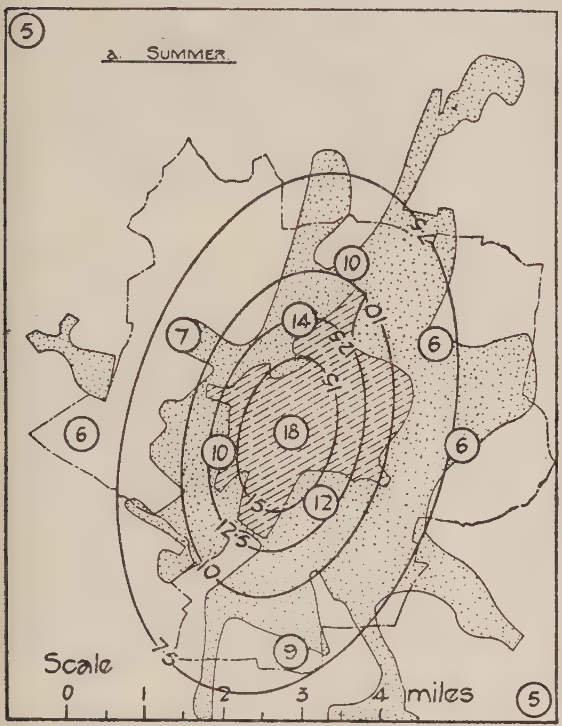


FIG. 3·46(a)

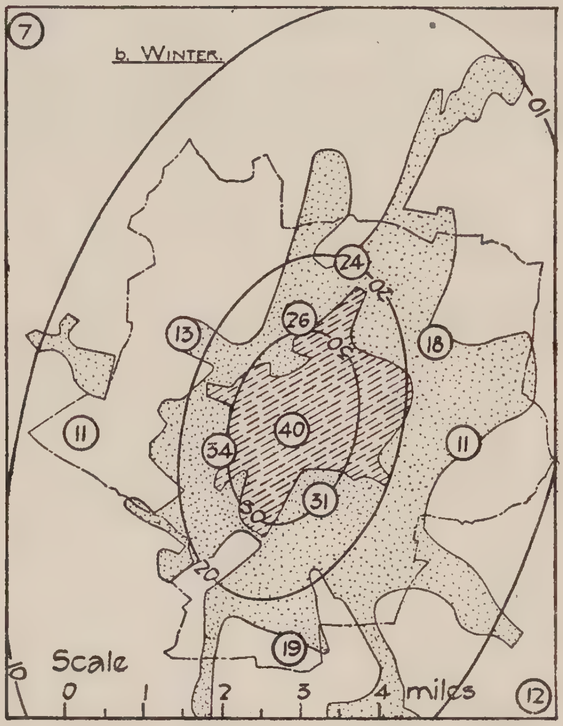


FIG. 3·46(b)

DISTRIBUTION OF SMOKE IN CALMS.

Concentration in arbitrary units for comparison with Fig. 3·41(a).

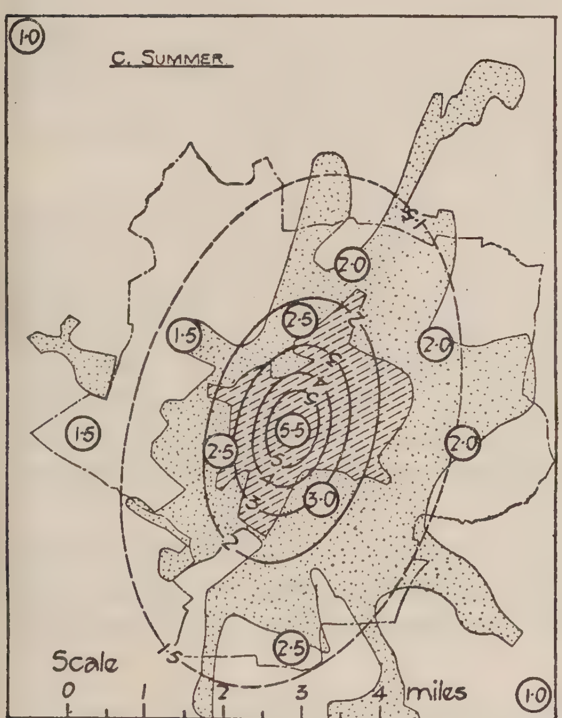


FIG. 3·46(c)

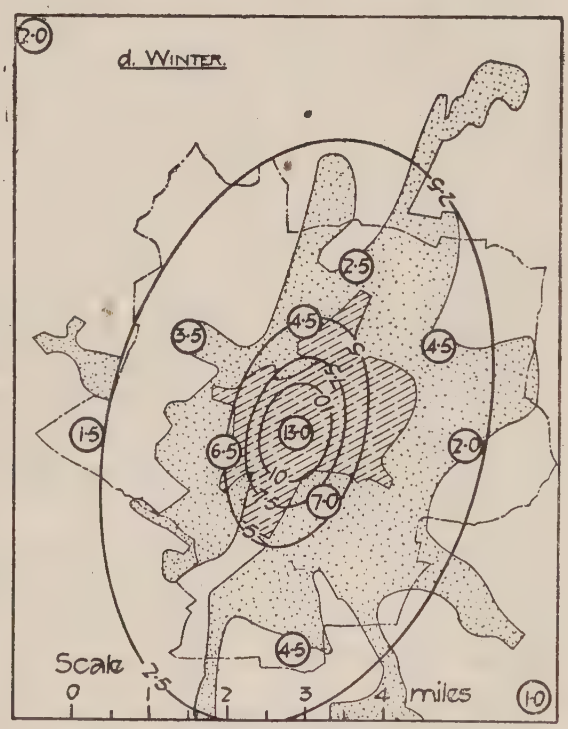


FIG. 3·46(d)

DISTRIBUTION OF SULPHUR DIOXIDE IN CALMS.

Concentration in arbitrary units for comparison with Fig. 3·41(c).

day's observations in calm weather. On the other hand the mean distribution of pollution can be ascertained with little difficulty in a few months. If now this mean distribution can be corrected by a slight empirical adjustment to represent the probable distribution in calms, a saving of time will be made.

A further advantage is that monthly observations, such as lead peroxide results, can be used instead of, or in conjunction with, daily observations.

3·47 *Country Pollution*

If Leicester ceased to be a smoke-emitting city, its air would be comparatively clean but still not perfectly clean. There would be some *exotic* pollution, i.e. coming from outside, in contrast with the *native* pollution for which Leicester itself is responsible. Estimates of Leicester's exotic pollution can be made from Tables 3·45, by considering stations in country districts other than those downwind from Leicester. The term *country pollution* will be used to represent the pollution which is in the wind before it reaches Leicester.

When there is a choice in tables 3·45 among several stations which are suitably placed to measure country pollution, the cleanest station will be chosen, since the others may have their own local pollution; indeed it is hard to find a place which is free from local pollution. In each row of percentages in Tables 3·45, the lowest pollution is in bold figures, and the next lowest in italics. In nearly every case the station so marked is one which could not possibly have been affected by pollution from Leicester. The occasional exceptions are station 11 in south-east winds and station 12 in north-west winds. Although these are the outermost stations, and although estimates of pollution in such dilutions are not very accurate, it is remarkable that pollution from Leicester should have so little effect 4¾ or 6 miles downwind. This has been made the subject of a separate investigation in Section 3·491.

The bold and italic figures in Tables 3·45 are the best estimates of country pollution which can be made from the data. They probably tend to be too high, since a small amount of local pollution will appreciably increase them. Unfortunately no simple way of getting better estimates has been developed. The best site for observations of country pollution would probably be the top of a high mast, so that the height of the mast as a minimum would separate the apparatus from the nearest sources of pollution. The standard deviation of each estimate of mean country pollution in tables 3·45 is from 20% to 35% of itself; this does not include persistent errors, but no local source of pollution would be expected to affect every observation.

In figures 3·47, estimates of country pollution relative to that of Central Leicester are plotted in the form of wind "roses." The length of each arm represents the country pollution in the appropriate wind, and is proportional to the lowest figure in the appropriate column of tables 3·45. The dot beyond the end of each arm represents the next lowest figure. The scale has been converted to absolute units, by multiplying with a factor which makes the mean for Central Leicester the same as in Fig. 3·41. The figures therefore represent country pollution on days when there were normal concentrations in Central Leicester.

It is at once apparent that westerly winds are generally dirtier than easterly winds, but it is well to check this and other conclusions by tests of significance (see Section 6·21). These tests have been used in drawing the following conclusions from figures 3·47:—

(1) The winds of each rose may be divided into two groups, N, NE, E, SE (easterly), and S, SW, W, NW (westerly). In each of the 10 roses the westerly group of winds is significantly more polluted than the easterly group.

Westerly winds contain about 1½ times as much smoke and sulphur dioxide as easterly winds.

(2) In winter, when the wind velocity exceeds 10 m.p.h. there is a significant reduction in the concentrations of country smoke and country sulphur dioxide, taken separately.

The magnitude of the reduction appears to be about 20%, i.e. a wind of greater than 10 m.p.h. would be expected to be about 20% cleaner than a wind of about 5 m.p.h. The reduction for sulphur dioxide is significant for easterly and westerly winds taken separately; for smoke it is significant for westerly winds only. The evidence as a whole is therefore in favour of the conclusion that this effect of wind velocity applies individually to all wind directions.

(3) The range of annual variation of country pollution is approximately the same in easterly as in westerly winds (i.e. the ranges are not significantly different).

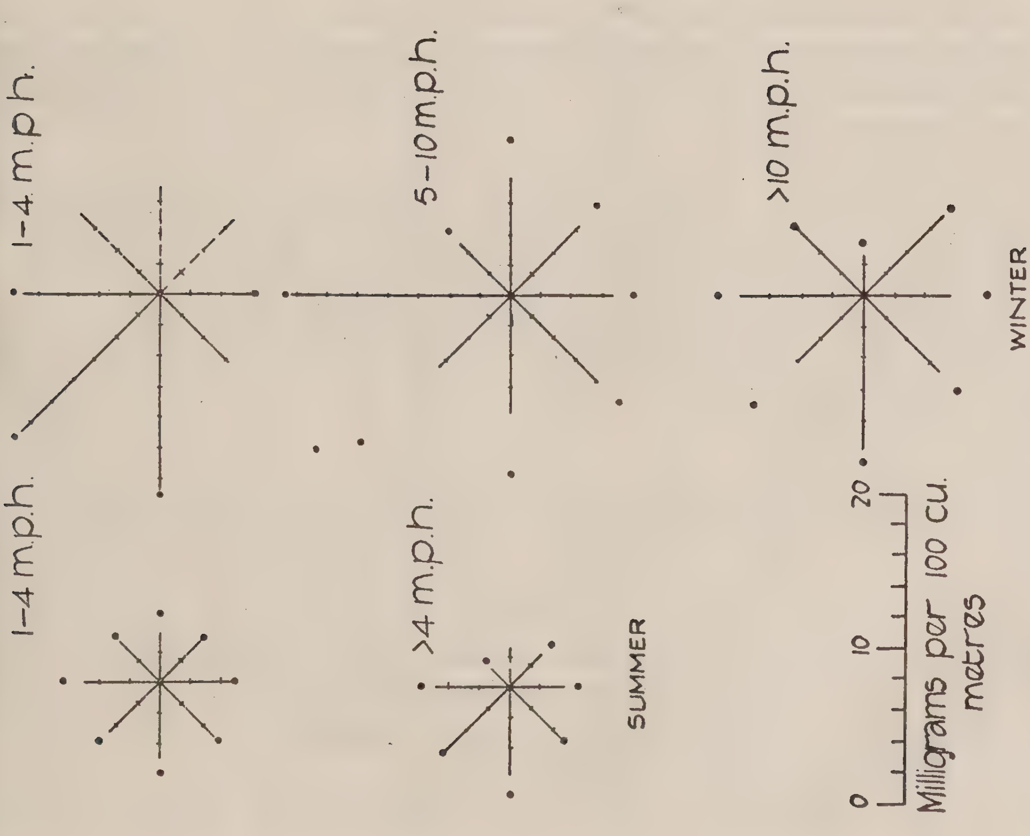


FIG. 3·47(a) SMOKE.

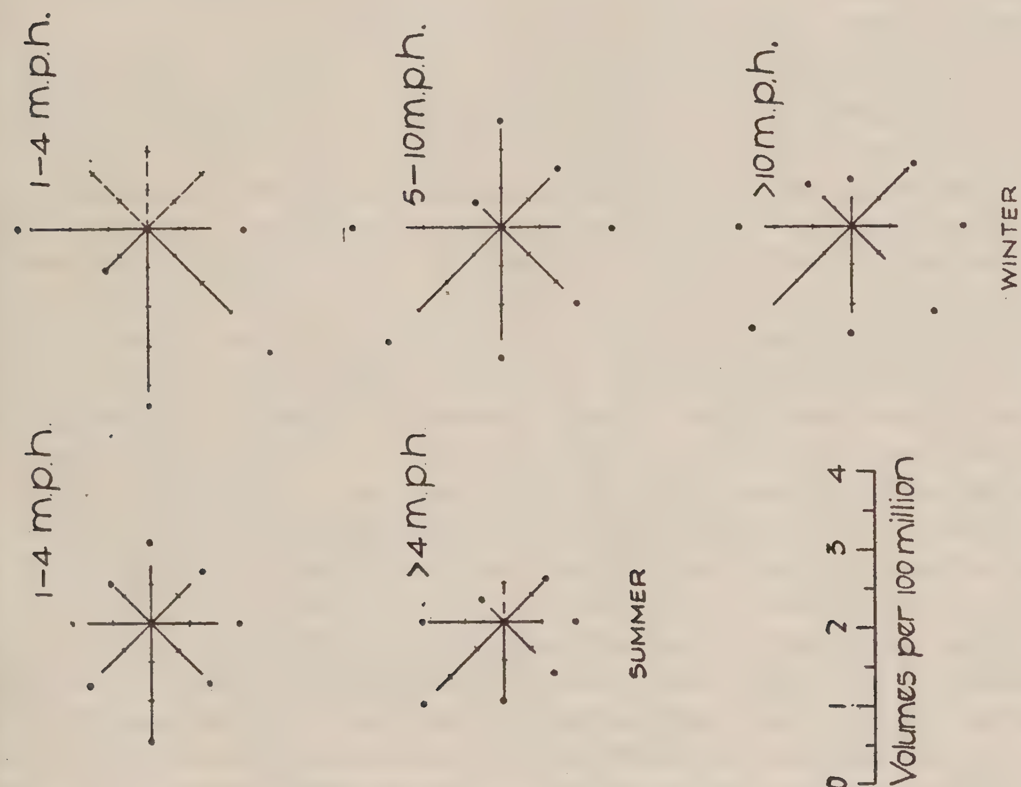


FIG. 3·47(b) SULPHUR DIOXIDE.

COUNTRY POLLUTION IN DIFFERENT WINDS.

The length of each arm represents the first estimate of country pollution in the appropriate wind. The dot beyond the end of each arm represents the second estimate. Dashes indicate shortage of data. Note particularly the relative cleanness of easterly winds.

(4) The ratio winter/summer for country smoke is significantly different from 1·0, being about 2·0. (For comparison, the corresponding ratio for smoke in Central Leicester is 2·5.)
(5) The ratio winter/summer for country sulphur dioxide is significantly different from 1·0, being about 1·5. (For comparison, the corresponding ratio for sulphur dioxide in Central Leicester is 2·3.)
(6) The ratio country/town is significantly greater for smoke than for sulphur dioxide, being about 1½ times greater. (This can best be seen by reference to tables 3·45.)
(7) Even in the centre of Leicester the wind-borne pollution is very considerable in relation to local pollution. At station 1, in fact, the wind-borne pollution ranges from 10% to 40% of the total.

To account for *conclusion* (1) it is necessary to examine a small-scale industrial map of England, such as that in the Times Atlas, which has been reproduced in Fig. 3.1a. There is a half-ring of industrial areas round Leicester from south-west to north at a radius of about 30 miles, including such towns as Coventry, Birmingham, Derby and Nottingham. The sector from north-east to south is practically clear of industry, except for a small district round Northampton in the south-east. At greater distances from Leicester are South Wales (120 miles SW), Staffordshire (50 miles NW), Lancashire (80 miles NW), West Riding of Yorkshire (60 miles N), and London (100 miles SE). Therefore if pollution from industrial areas travels 30 miles or more downwind, the country pollution roses are likely to be asymmetrical. This indeed seems to be the true explanation of conclusion (1), and there are visual observations to support it. For instance, in Oxfordshire in north winds a smoke pall is frequently seen to arrive in the afternoon, as if it had been produced in the Midlands at 8-10 a.m. and drifted 60 miles downwind. Yet this result will have to be compared with the statement in Section 3·493 that it is difficult to observe the pollution produced by Leicester even 4 miles downwind. Contradictory as these results appear to be, they are well substantiated, and will be shown to be reconcilable in Sections 3·493 and 5·12. The fact remains (*conclusion* 6 above) that of the pollution measured in Central Leicester, within 1 mile of the city centre, from 10% to 40% originates outside Leicester; the actual percentage depends upon the wind direction and the time of year.

Conclusion (2) is interesting, because the wind appears to have some effect in diluting country pollution. If dilution were the only factor, a 10-m.p.h. wind would be twice as clean as a 5-m.p.h. wind. This is not the case, and a suggestion why is given in Section 4·711.

Conclusion (3) suggests that the pollution in easterly winds must be formed in the same way as pollution in the industrial areas to the west of Leicester. It might have been formed in the villages and towns of the east midlands, or some of it might have originated in the industrial regions of Germany.

Conclusion (4) indicates that the chief source of country smoke has the same annual variation as the chief source of the smoke in Central Leicester. The simplest explanation would be that in both country and town the chief source of smoke is the domestic grate.

Conclusion (5), on the other hand, indicates that the sources of the sulphur dioxide in Leicester and in its surrounding country must have different annual variations. The simplest explanation would be that in Leicester considerably more coal is burned for heating in winter than for operating machinery; whereas country air derives a much greater proportion of its sulphur dioxide from (distant) industries. The effect of ammonia on the volumetric method is a complication, but it is difficult to see how ammonia could account for conclusion (5).

Conclusion (6) might indicate that ammonia neutralizes a considerable proportion of the sulphur dioxide in country air.

Conclusion (7) is a warning that, even in our great cities, exotic pollution cannot be neglected if accuracy is required.

The Leicester Survey was not designed to attack the problems of country pollution in the most efficient manner, and the results of this section must be regarded simply as a by-product. But they produce interesting speculations about the distances travelled by pollution and suggest that pollution might well be investigated in places such as the east coast, the Atlantic Ocean and the western limit of the Clyde estuary. For the main purpose of the survey, however, it was important to distinguish between native Leicester pollution and exotic pollution, and that is the chief reason for this section. Its results will be applied in the next section to the more practical question of what happens to the pollution produced by Leicester.

3·48 *Native Leicester Pollution*

The country pollution discussed in the previous section is what would be observed at each of the 12 stations if Leicester were not there. Subtracting the country pollution from the actual pollution observed gives what would be observed if the incoming air were pure, and only native pollution were measured. The word native may be taken to apply anywhere within about ten miles of the centre of Leicester. It is doubtful whether Loughborough, nine miles north-north-west of Leicester, contributes to the native pollution or the country pollution on the above treatment, but since even Leicester's pollution cannot be easily detected more than four miles downwind this doubt is unimportant.

Figures 3·48a-j represent estimates, in the form of wind roses, of native Leicester pollution deduced from tables 3·45. The appropriate estimate of country pollution was subtracted from each column in the tables; then the columns were made comparable by multiplying each by a factor to make the mean for Central Leicester 100% in each column. This step is only valid if it is known that there is no wind directional effect on stations 1, 2, 3, 4 as a whole; a separate investigation had been made which showed that, within an accuracy of about 10%, no directional effect is observable on the mean of stations 1, 2, 3, 4, Figures 3·48a-j are therefore only accurate to about 10%. For the sake of completeness, wind roses have been included for stations 13, 14 and 15, where sufficient observations were available for their estimation. The observations for these wind roses were made from May to December, 1939; at the remainder of the stations observations from May, 1937, to March, 1939, were used. Inset on each map is a wind rose representing the appropriate country pollution on the same scale, i.e. taking the mean native pollution in Central Leicester as 100%. Each map now represents the entire data of one section of tables 3·45, divided into an estimate of country pollution and estimates of native Leicester pollution at 12 stations. The wind roses at stations 13, 14 and 15 have been derived from additional data.

The striking result in the figures is the tendency of the longer arms of the suburban stations all to point inwards. The roses of stations 2, 3, and 4 also point more inwards than outwards, while station 1 is symmetrical. A closer inspection of the figures reveals that the effect of Leicester's pollution is relatively more noticeable at the suburbs, $1\frac{1}{2}$ to 3 miles from the centre, than anywhere else. At any suburban station, a sudden reversal of wind so that the wind blows directly from Leicester may send up the native pollution about five-fold, or the actual pollution about two-fold. At stations 2, 3, 4, and 14, all about one mile from the centre, a similar change of wind would only increase the native or actual pollution $1\frac{1}{2}$- to 2-fold.

The wind roses at stations 11, 12, 13, and 15 are too small, both in themselves and in relation to the rose of country pollution, to give clear evidence of the effect of native Leicester pollution in country districts. Better evidence can be got by examining the individual daily records, and by estimating for each day separately the amount of native pollution at each country station. This has been done in Section 3·492.

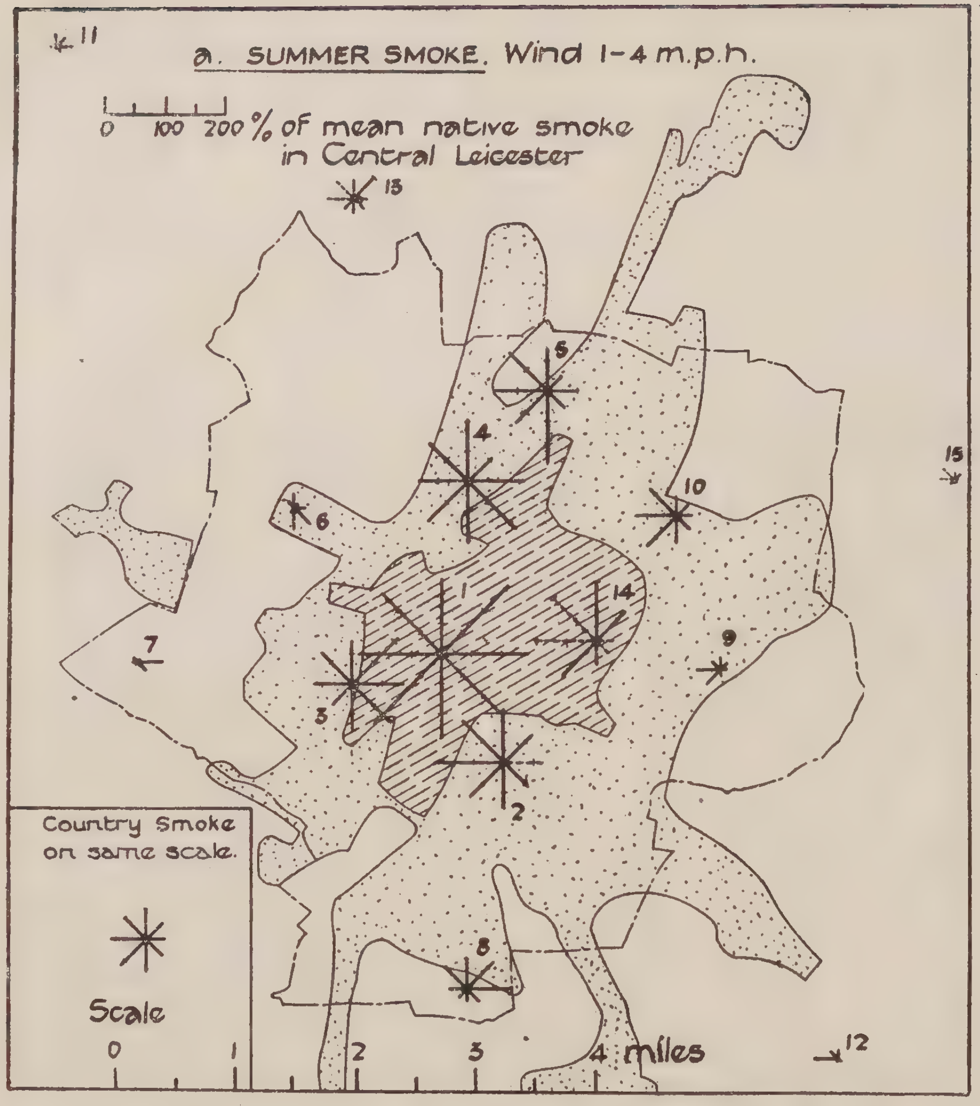


FIG. 3·48(a) NATIVE LEICESTER SMOKE—LIGHT WINDS, 1-4 M.P.H.—SUMMER.

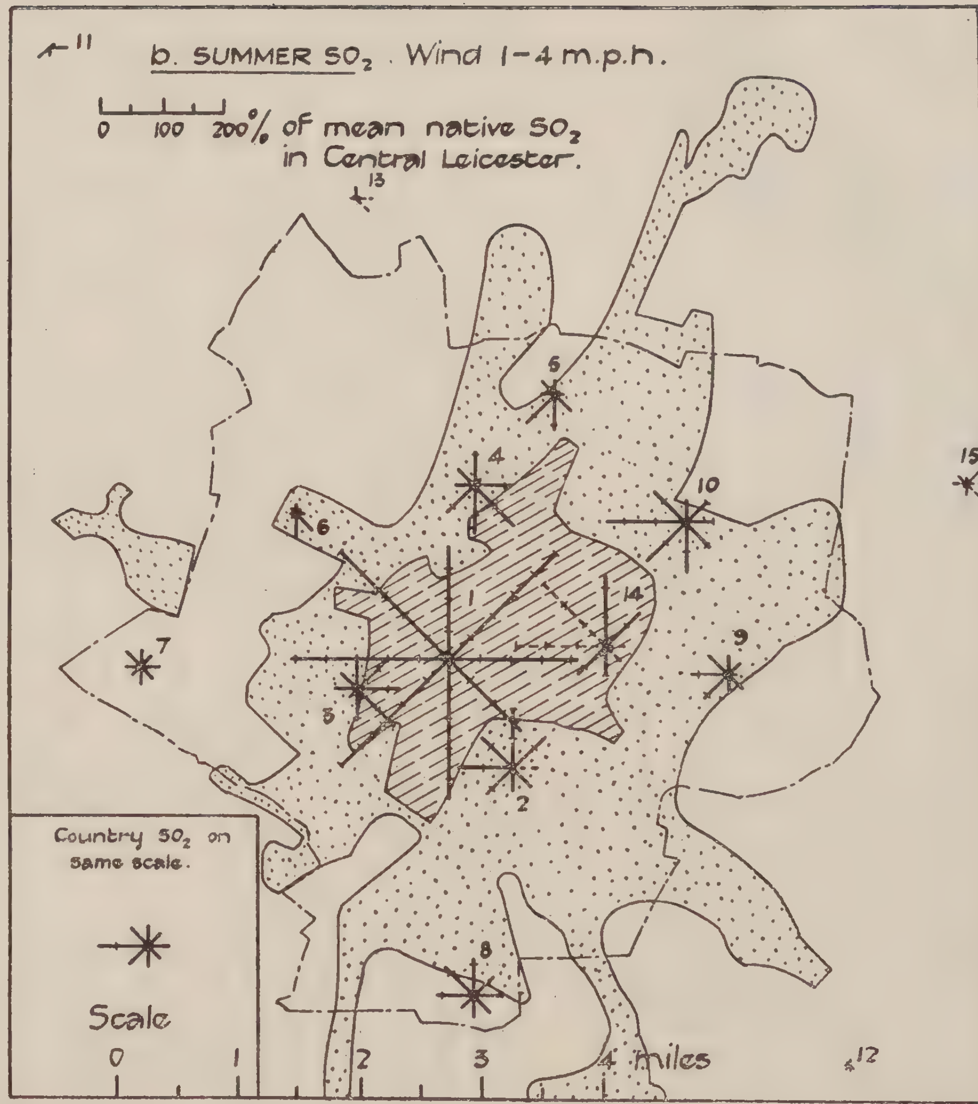


FIG. 3·48(b) NATIVE LEICESTER SULPHUR DIOXIDE—LIGHT WINDS, 1-4 M.P.H.—SUMMER.

The wind roses are estimates of smoke which would be observed at each station, in each wind, if the air were pure before reaching Leicester. The concentrations of smoke which were actually found in the air before reaching Leicester are given as a wind rose in the inset.

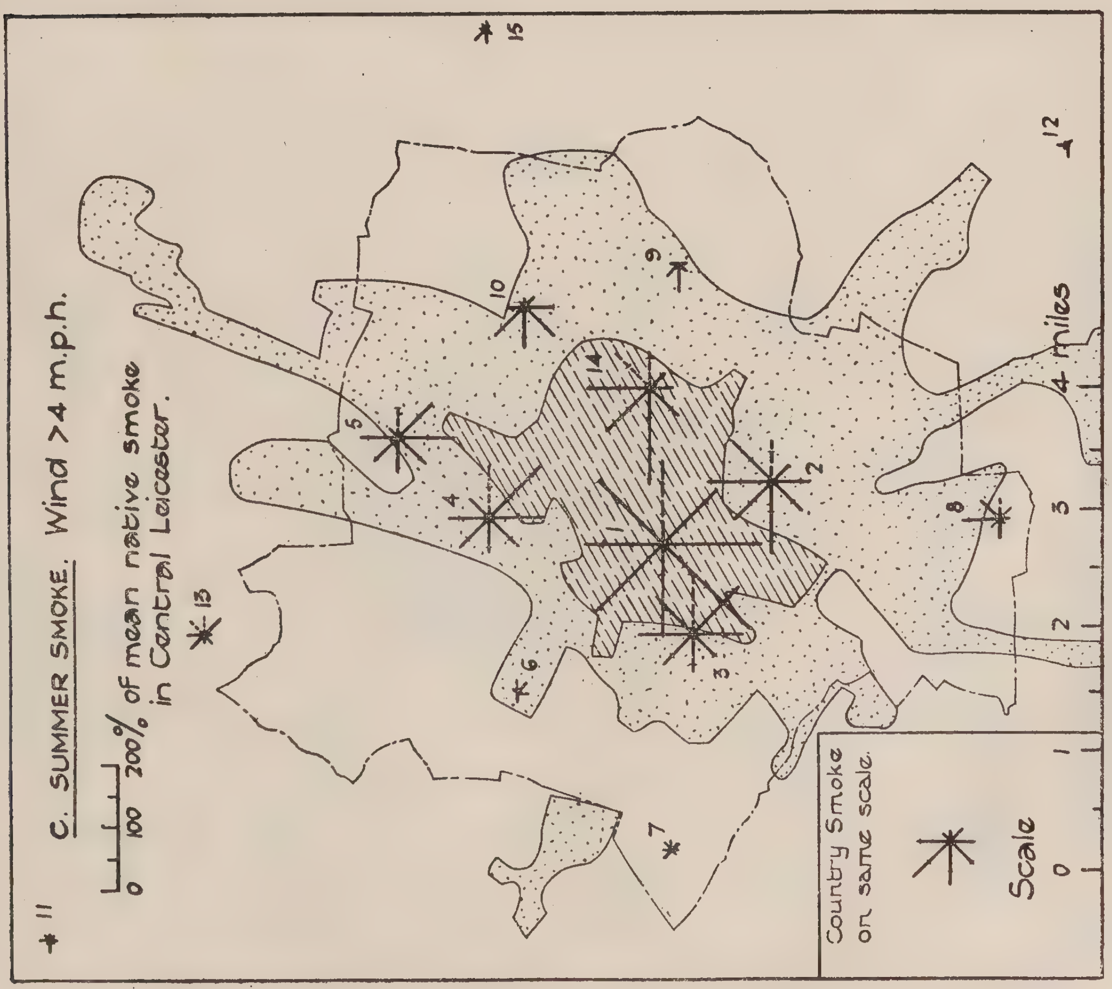


FIG. 3·48(c) NATIVE LEICESTER SMOKE—MODERATE WINDS >4 M.P.H.—SUMMER.

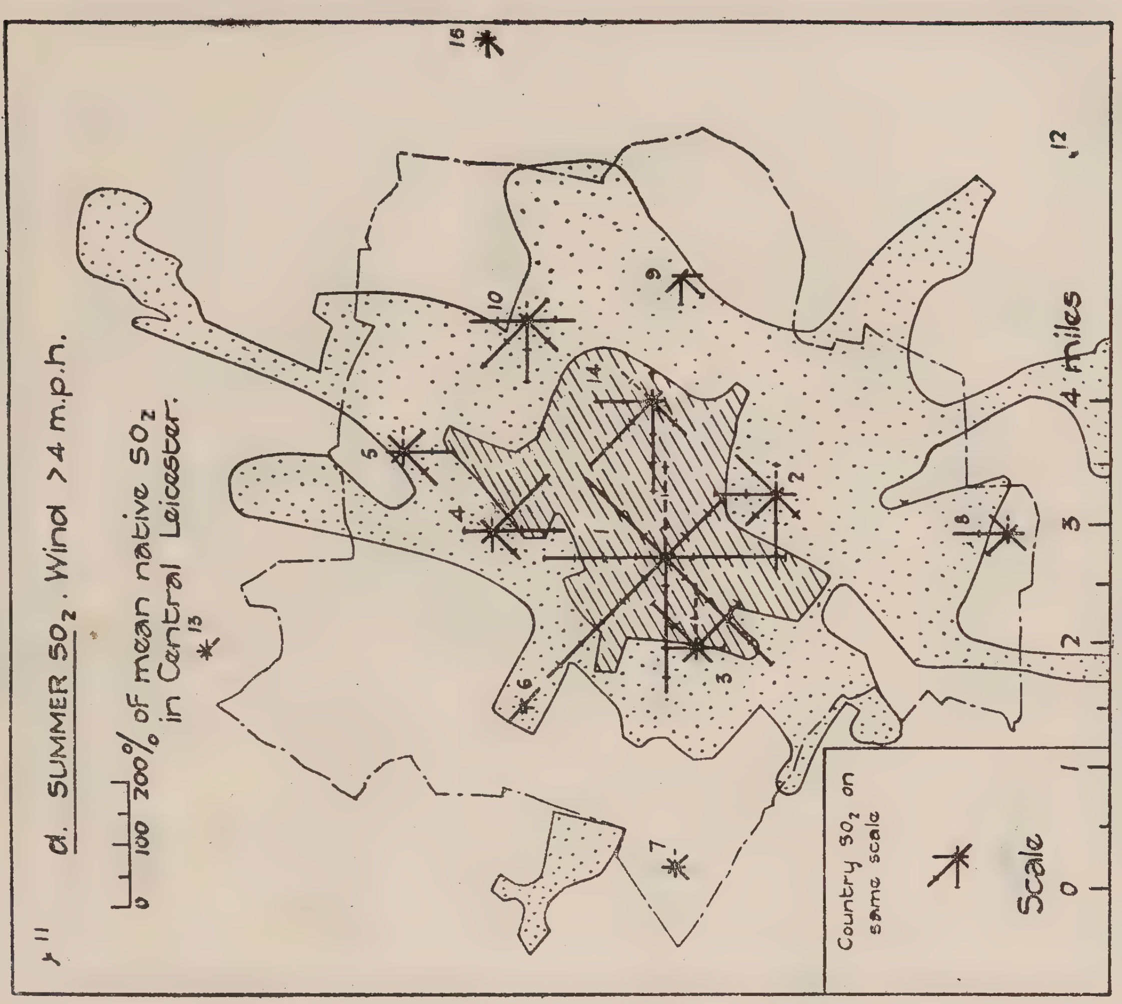


FIG. 3·48(d) NATIVE LEICESTER SULPHUR DIOXIDE—MODERATE WINDS >4 M.P.H.—SUMMER.

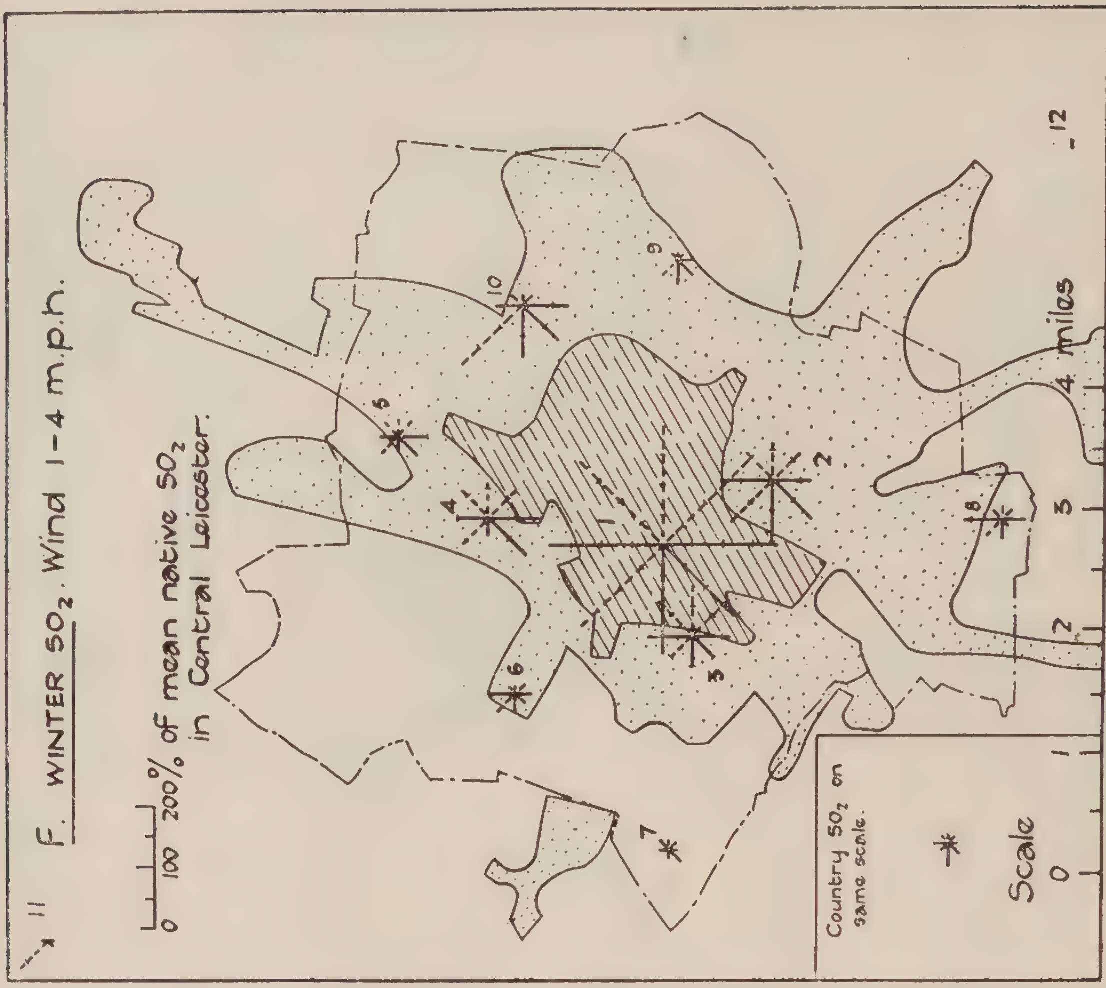


FIG. 3·48(f) NATIVE LEICESTER SULPHUR DIOXIDE—LIGHT WINDS, 1-4 M.P.H.—WINTER.

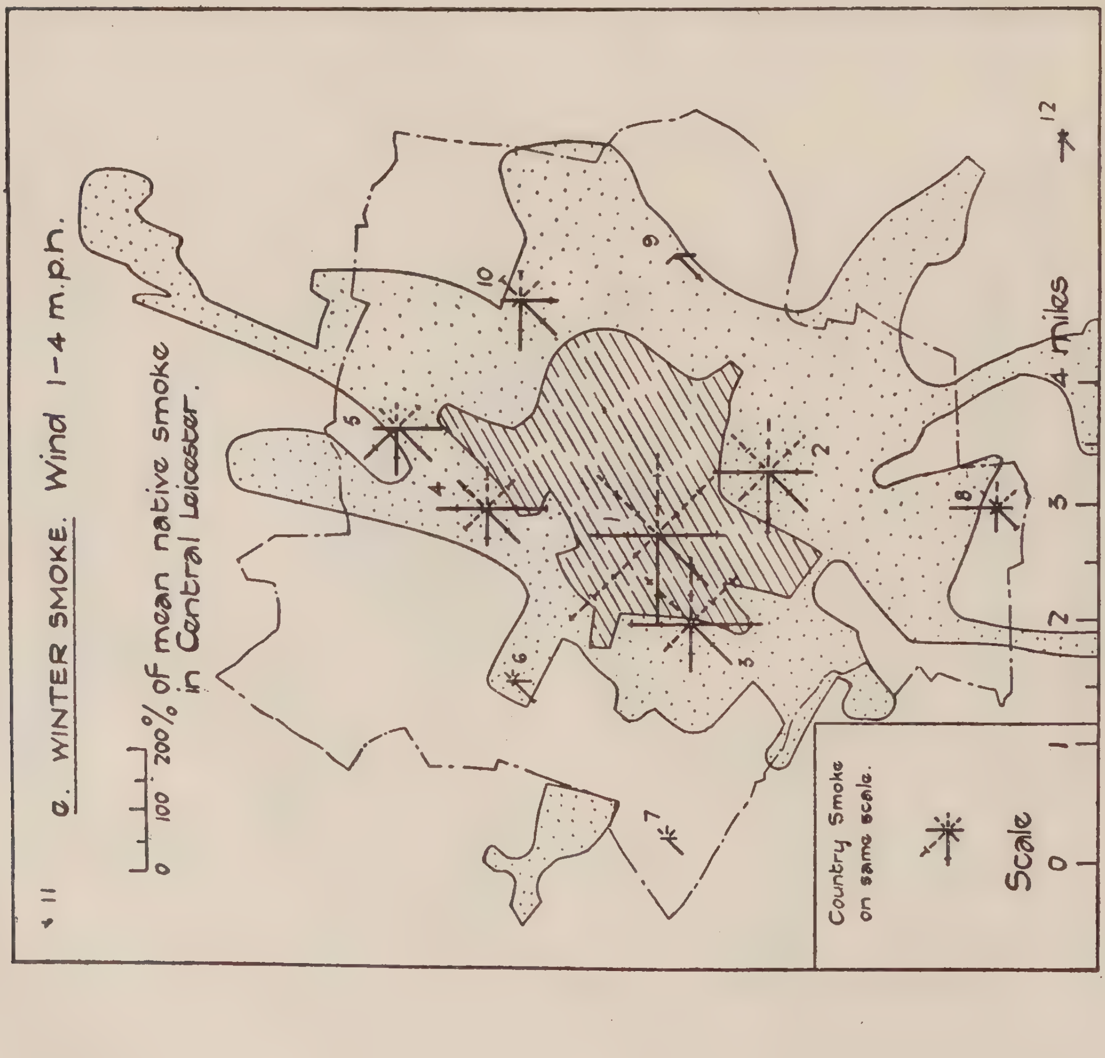


FIG. 3·48(e) NATIVE LEICESTER SMOKE—LIGHT WINDS, 1-4 M.P.H.—WINTER.

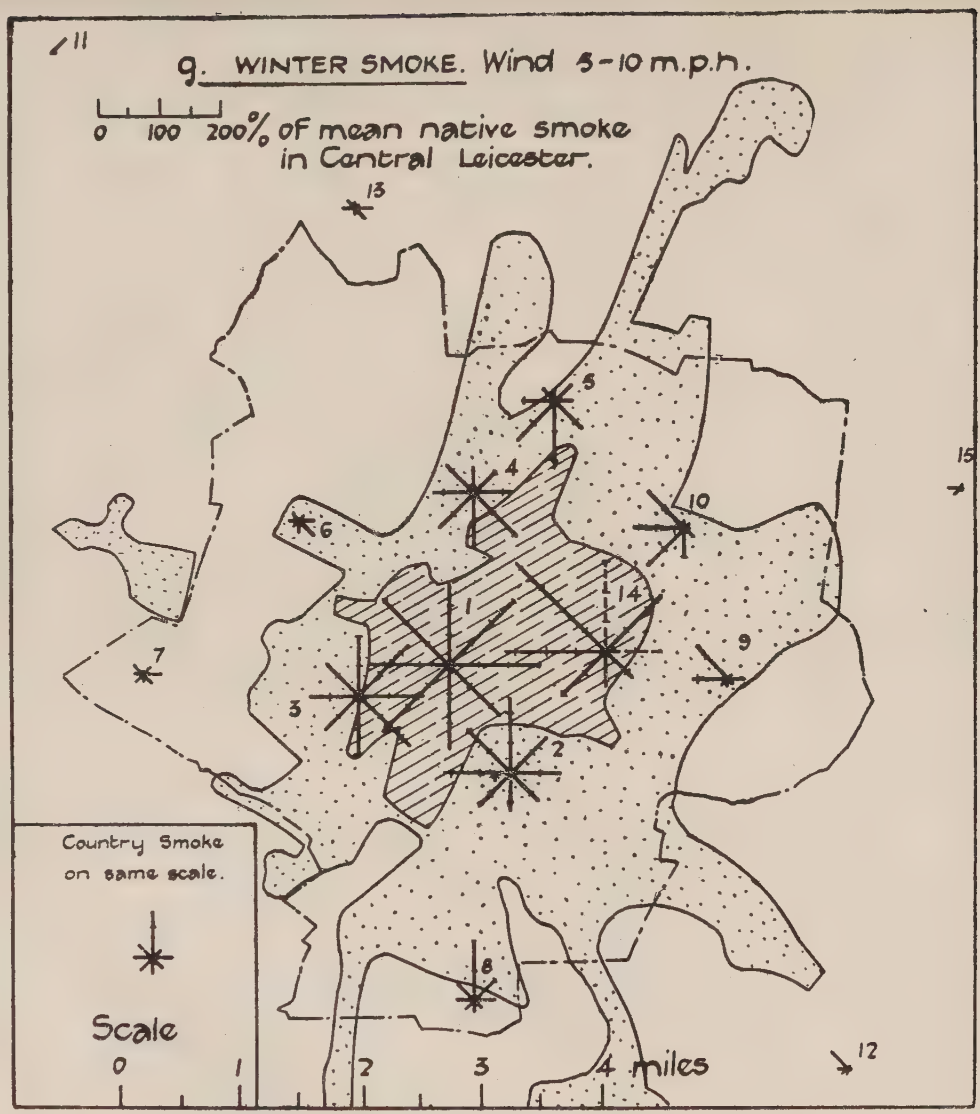


FIG. 3·48(g) NATIVE LEICESTER SMOKE—MODERATE WINDS, 5-10 M.P.H.—WINTER.

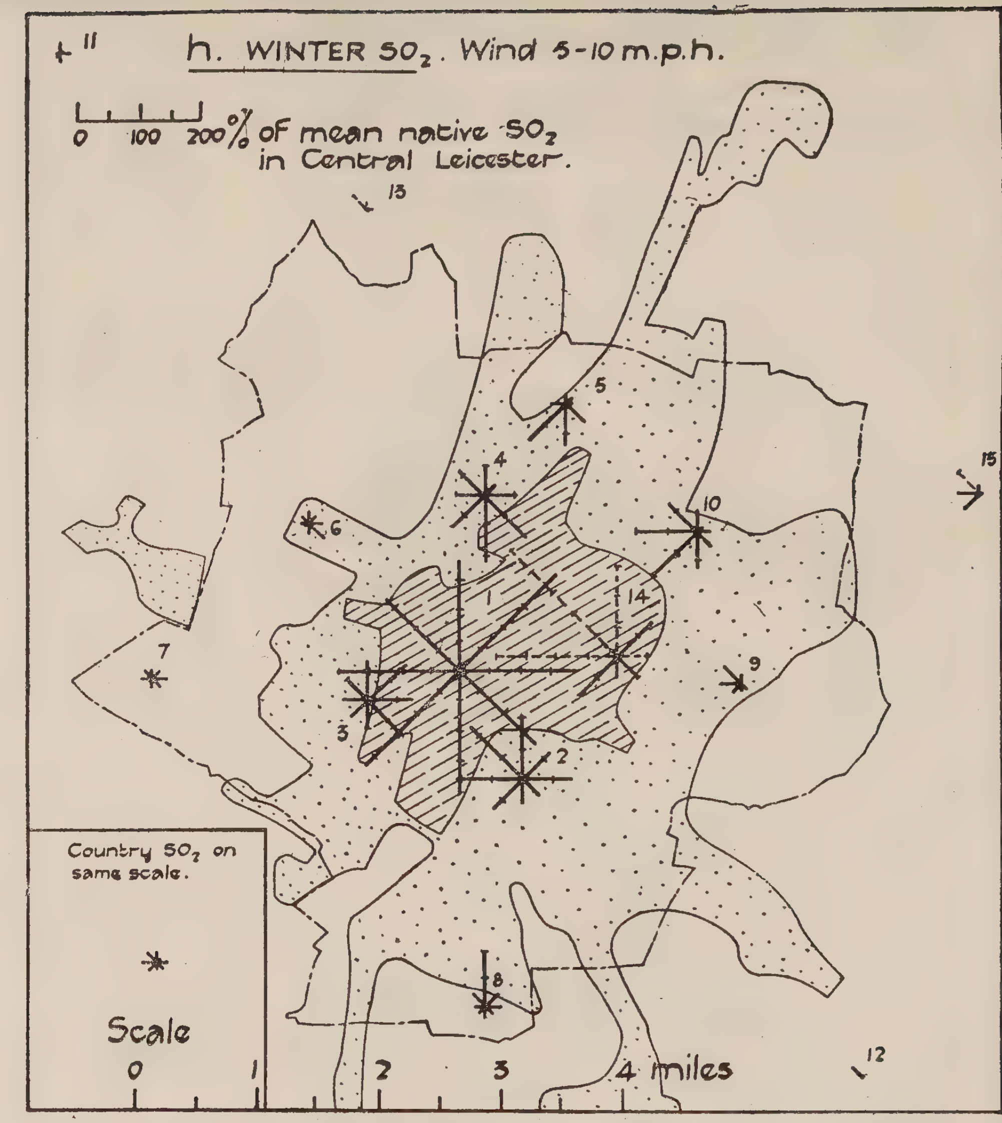


FIG. 3·48(h) NATIVE LEICESTER SULPHUR DIOXIDE—MODERATE WINDS, 5-10 M.P.H.—WINTER.

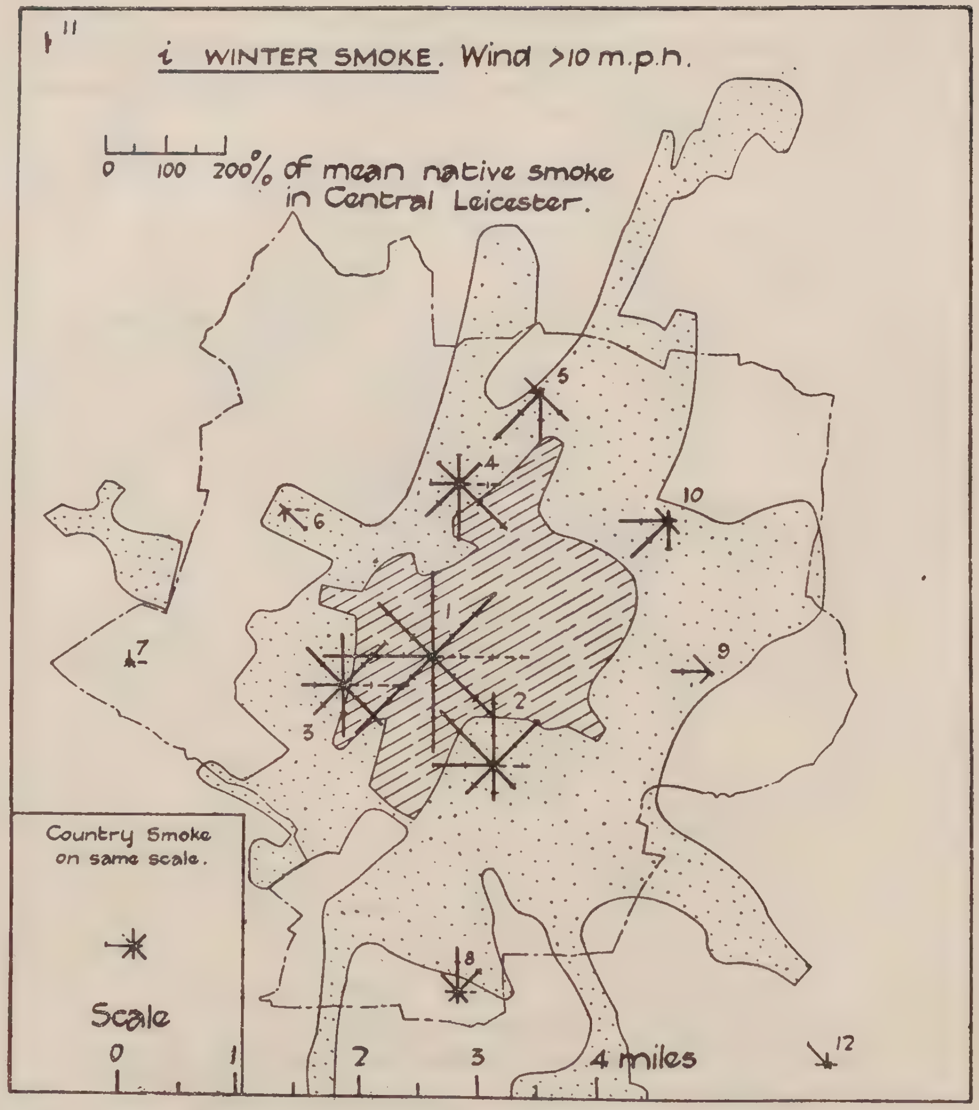


FIG. 3·48(i) NATIVE LEICESTER SMOKE—FRESH WINDS > 10 M.P.H. —WINTER.

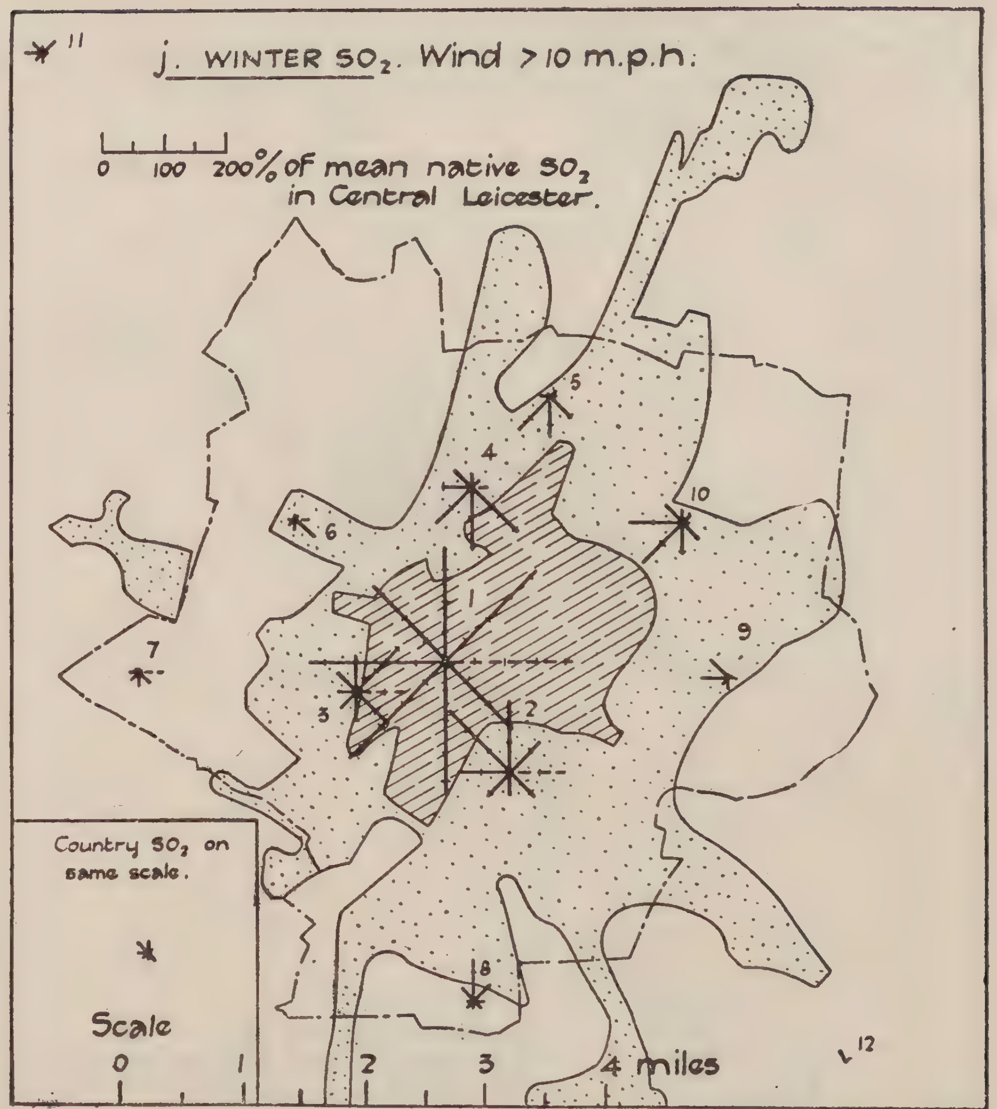


FIG. 3·48(j) NATIVE LEICESTER SULPHUR DIOXIDE—FRESH WINDS > 10 M.P.H.—WINTER.

3·49 *Composite Maps*

Taking one wind direction at a time in each map of figures 3·48, a contour map, similar to figures 3·41, could be drawn representing the distribution of native Leicester smoke or sulphur dioxide in the particular wind and season dealt with by the map. Eight such maps would be made from each map of figures 3·48, and each might be expected to show a drift of pollution concentrations downwind, and possibly other effects as well. A more rigorous and less clumsy way of showing up the effect of wind direction on pollution is to form a composite map from each group of eight wind directional maps. This treatment has the advantage of smoothing out the irregularities of Leicester as a source of pollution, and replacing it by a symmetrical circular source.

Figs. 3·49 a and b are the results, given separately for smoke and sulphur dioxide. Results are again on the scale where the mean native pollution for Central Leicester is taken as 100%. All the data of Figs. 3·48a-j have been used, but it has been impossible to include individual numbers in these reproductions. There was considerable uncertainty in drawing the isometric lines of figures 3·49, and there was no justification for drawing in them any more complicated shapes than circles. The accuracy of position of the different contours 20% to 100% is estimated as follows:—

Contour	20%	40%	60%	80%	100%
Standard deviation in miles ..	0·5	0·4	0·2	0·3	0·3

These are the average standard deviations over the 10 maps in figures 3·49. The contours 120%, 140%, etc., are less accurate, but are included in the maps to assist in visualizing the distributions.

With the above standard deviations as a basis, it is possible to establish the statistical significance of the following conclusions:—

(a) Pollution is greatest downwind and least upwind from the centre.
(b) As the wind velocity increases the upwind contours move nearer to the centre by distances up to 1 mile.
(c) As the wind velocity increases the downwind contours move outwards from the centre by distances up to $\frac{3}{4}$ mile.
(d) As the wind velocity increases the crosswind contours approach the centre by distances up to 1 mile.
(e) There are no significant differences in radii of the contours as wind velocity increases.

Conclusions (a) to (e) may be summarized by saying that as the wind velocity increases the contours move downwind by distances up to 1 mile, without altering their radii.

(f) There is no significant shifting downwind of the point of maximum concentration (i.e. the point of maximum concentration never moves more than $\frac{1}{2}$ mile from the centre of Leicester as a result of wind).

These results are very much less striking than had been expected. There is no doubt, however, that they truly represent the effect of wind on urban pollution near street level, on days of average weather. If an inhabitant of Leicester wanted a breath of appreciably cleaner air he would do about as well by walking a mile upwind from the Town Hall as by walking three miles downwind, unless the wind happened to be very light. Possibly an even shorter way to purer air would be vertically upwards in a balloon, but no measurements were made of the pollution in the air above Leicester.

In view of the small displacements of the circles in figures 3·49, it is important to consider other observational evidence that pollution escapes from a town

by travelling downwind. We all know that it does, because we have seen smoke trails from chimneys, but if so, why is the most polluted part of Leicester so short a way downwind from the centre? There are two methods of approach to this question, using the observations of the Leicester Survey.

One is to pick out days when turbulence was not sufficient for rapid upward escape of pollution, and examine whether on these days pollution was accumulated in the surface air as it blew through the town. There were 15 days, all in winter, when the smoke in Central Leicester was more than 2·5 times its normal concentration, and the absence of vertical mixing on these days is confirmed by the strong positive temperature gradients recorded at Mildenhall. Composite maps of smoke and sulphur dioxide concentration were constructed from the 15 days' results, but while there were a number of exceptionally high relative concentrations of pollution in the suburbs, these were not always

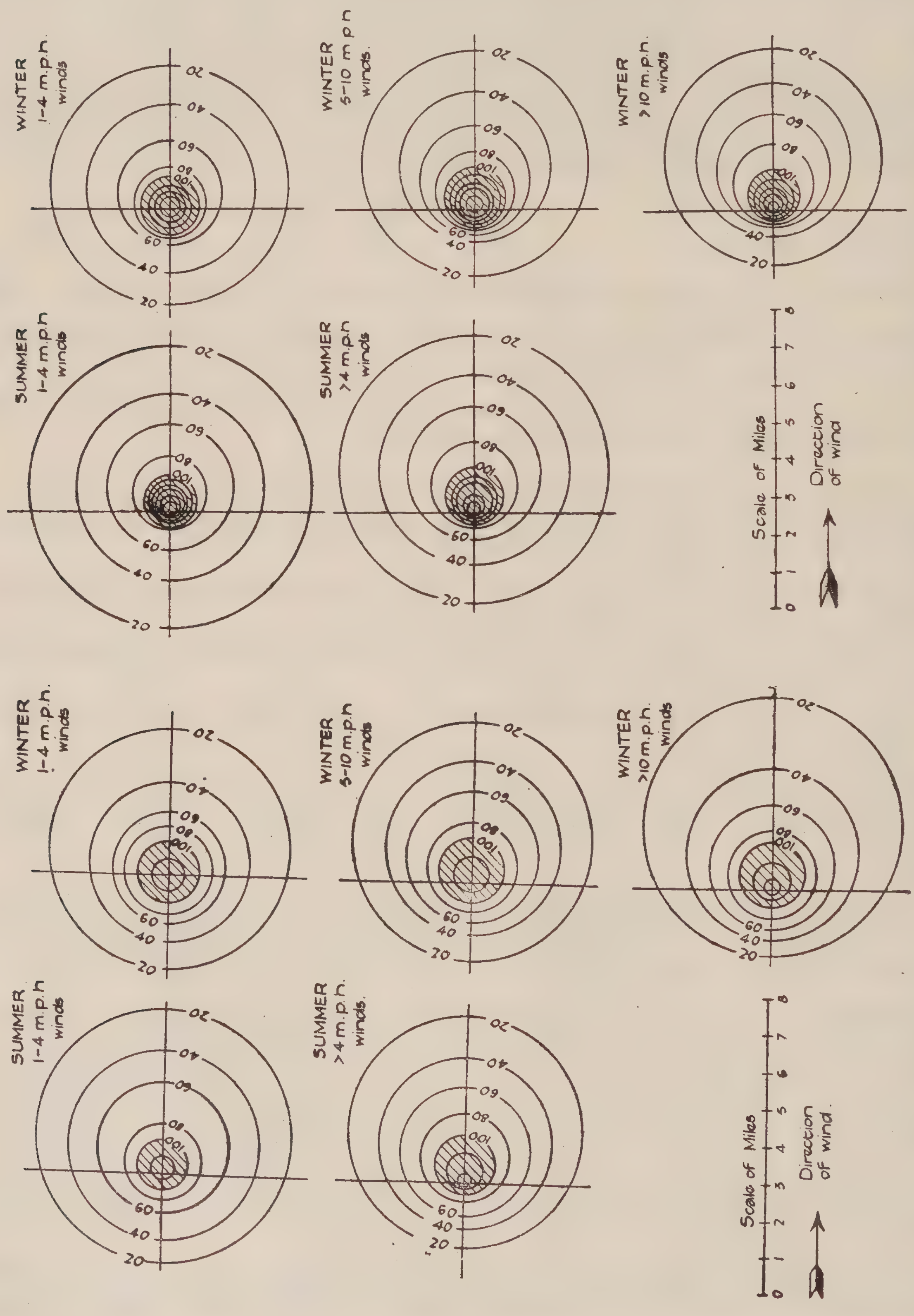


FIG. 3·49(a) NATIVE LEICESTER SMOKE. FIG. 3·49(b) NATIVE LEICESTER SULPHUR DIOXIDE.
Effect of wind velocity on pollution in a symmetrical town the same size as Leicester. The mean for Central Leicester is taken as 100.

downwind from the centre of Leicester, according to the average wind direction recorded at station 9. The winds were usually very light, and local currents most probably occurred. In consequence, the composite maps did not provide conclusive proof that the downwind suburbs are on special occasions more polluted than the centre of the town. The maximum smoke concentration on the composite map was ½ to 1 mile downwind, and the maximum concentration of sulphur dioxide was less than ½ mile downwind from the centre, so conclusion (f) above is true under almost any conditions.

3·491 *Composite maps of ultra-violet daylight.* The other approach is based on the assumption that, if pollution does not accumulate in the surface air blowing through a town, then it must be rapidly escaping into the air above the town. (Escape of smoke and sulphur dioxide by deposition may be neglected.) The only observations which were influenced by pollution above Leicester were measurements of the daily total ultra-violet daylight. It is shown in Sections 3·42 and 4·23 how, in winter, the presence of smoke is associated with losses of daylight, and it is evident that daylight is reduced by smoke at all heights as well as near the ground. The distribution of daylight in a given wind may therefore be very different from the distribution of surface smoke.

The instruments used at Leicester were not accurate enough to measure the daily loss of ultra-violet daylight in summer, and the investigation was confined to the weekdays of ten winter months, November to March, 1937-8 and 1938-9. There being only one country station equipped with ultra-violet daylight apparatus, it was necessary to make use of observations at the suburban stations 5, 6, 7, 8, 9 to provide an estimate of how much daylight would have been received each day in the absence of smoke. The stations were divided into three groups: station 1; stations 2, 3, 4 (inner); and stations 5, 6, 7, 8, 9, 12 (outer). For any given wind direction the second and third groups were subdivided into *downwind* (within 22½° of downwind from station 1); *adjacent* (between 22½° and 67½° from the downwind direction); and *other.* For each day, the mean of the *outer other* stations was taken as representing the daylight which would have been received in the absence of smoke. The readings at all stations were then expressed as differences from this mean. (It was pointed out in Section 2·721 that these readings are on a logarithmic scale, where $k = 0{\cdot}043$ and a difference of 1 unit represents an increase or decrease of light in the ratio 1·0 to 0·906.)

Each day's observations were put into one of three groups, according to the daily mean wind velocity, and after tabulating, the various estimates of loss of daylight at each position relative to the wind direction and the centre of Leicester were averaged. The results are given in Table 3·491.

TABLE 3·491 *Mean loss of ultra-violet daylight on winter weekdays*

Loss is expressed in logarithmic units, and 1 unit represents a loss, due to smoke, of 9·4% of the possible daylight.

Wind Velocity	1 to 4 m.p.h.			5 to 10 m.p.h.			>10 m.p.h.		
	No. of obs.	Loss	Std. Error	No. of obs.	Loss	Std. Error	No. of obs.	Loss	Std. Error
Station 1	19	4·7	±0·9	47	3·9	±0·3	86	3·3	±0·4
Inner downwind ..	12	4·5	±0·8	26	5·6	±0·7	34	4·6	±0·5
Inner adjacent ..	13	2·4	±1·2	30	4·3	±0·8	57	2·4	±0·5
Inner other.. ..	19	2·1	±0·7	53	2·4	±0·7	102	2·2	±0·7
Outer downwind ..	13	3·6	±1·1	33	3·2	±0·8	36	2·6	±0·4
Outer adjacent ..	19	2·0	±0·7	62	1·1	±0·5	119	0·9	±0·3
Outer other ..		0·0			0·0			0·0	

Inner: Stations 2, 3 and 4, their average distance from Station 1 being 1·2 miles.
Outer: Stations 5, 6, 7, 8, 9 and 12, their average distance from Station 1 being 2·8 miles.

The standard errors of the estimates of loss are higher than would be desired but it is evident from the table that there were significant losses of daylight compared with the *outer other* stations, at all the remaining stations. Fig. 3·491 presents the results in a form suitable for comparison with Fig. 3·49a, and it leaves no doubt that the maximum loss of daylight occurs on an average at a point from ½ to 1½ miles downwind from the centre of Leicester.

While Fig. 3·49a represents the distribution of native Leicester *surface* smoke, Fig. 3·491 may be regarded as representing the distribution of native Leicester *total* smoke, and the difference between the two figures is striking. Evidently the hypothesis is correct that smoke tends to spread quickly upwards from the surface, thereby ensuring that the highest surface concentrations of smoke are

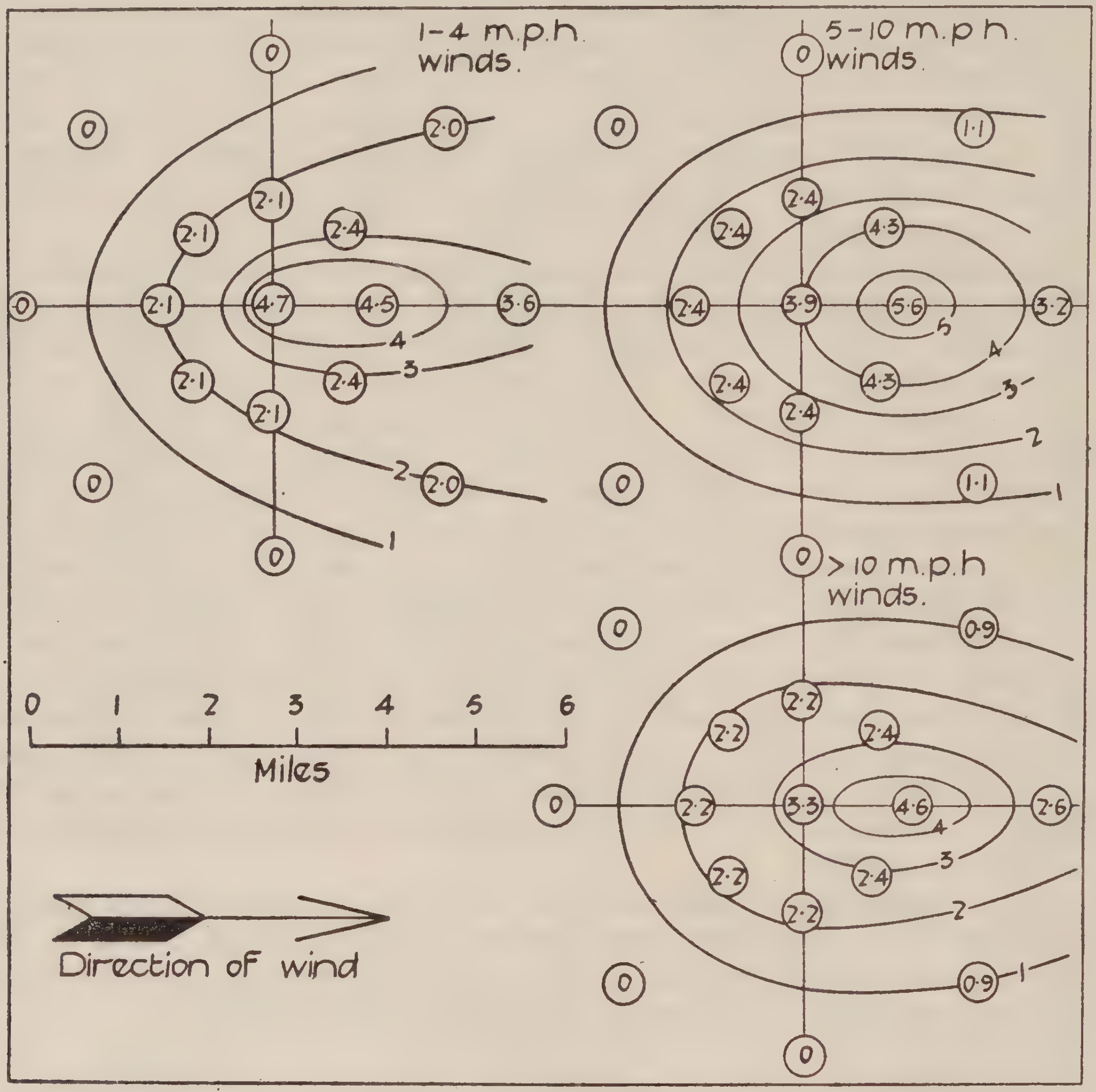


FIG. 3·491 EFFECT OF WIND VELOCITY ON ULTRA-VIOLET DAYLIGHT.
Expressed in logarithmic units; one unit represents a loss, due to smoke, of 9·4% of the possible daylight.

normally to be found in the districts where most smoke is generated. When once the smoke has left the surface layers, the stronger winds which it encounters will blow it rapidly away horizontally. There must also be considerable lateral diffusion, for otherwise the maximum losses of daylight in Fig. 3·491 would occur still farther downwind.

3·492 *Spreading downwind* of pollution near the ground may be considered from the downwind vertical sections of the maps in figures 3·49. Sections of this type are shown in the main curves of Figs. 3·492 a and b. In them, the ordinates are the concentration of pollution as a percentage of the mean native pollution for Central Leicester, and the abscissae are distance from the centre of Leicester in miles. The curves show very well the asymmetry of distribution which is

brought about by the wind. From the table in Section 3·49 the standard deviation of the abscissae varies from 0·2 to 0·5 mile, but it probably differs on the two sides of the origin. A simpler picture of the reliability of the curves

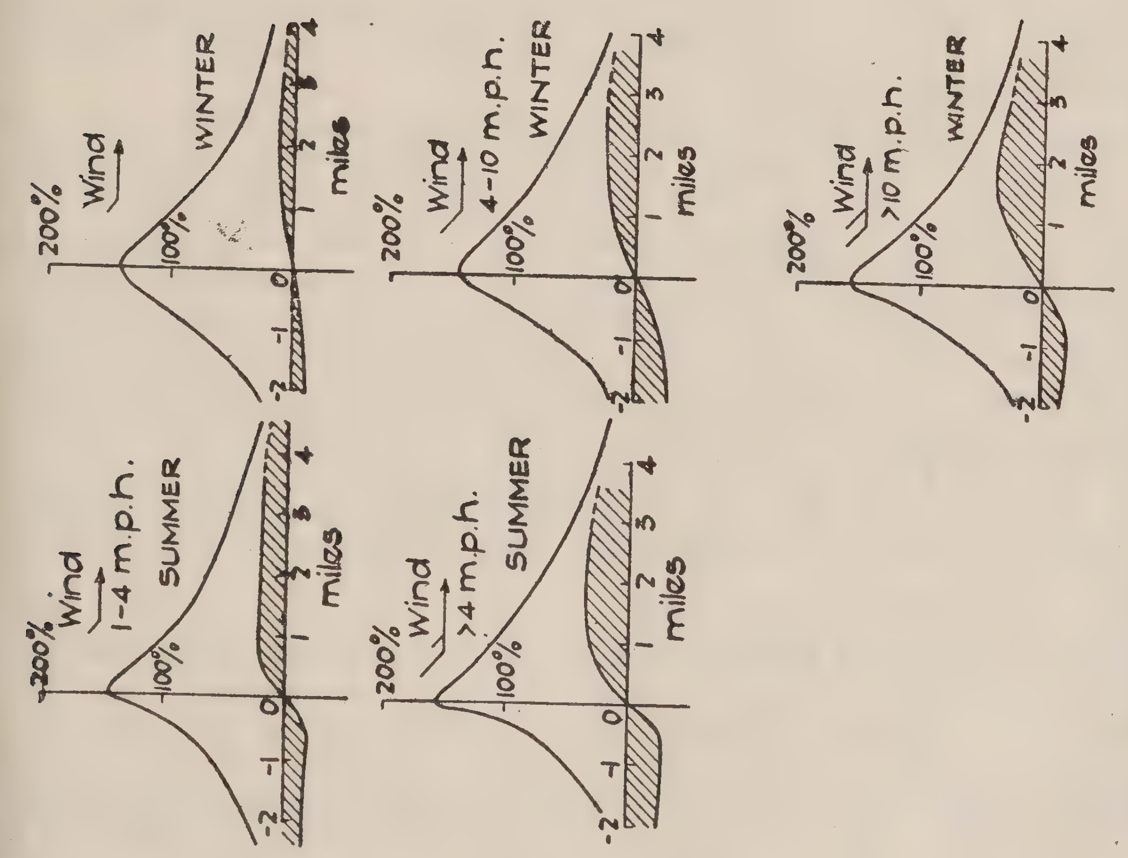


FIG. 3·492(a) SPREADING OF SMOKE UP AND DOWN WIND.

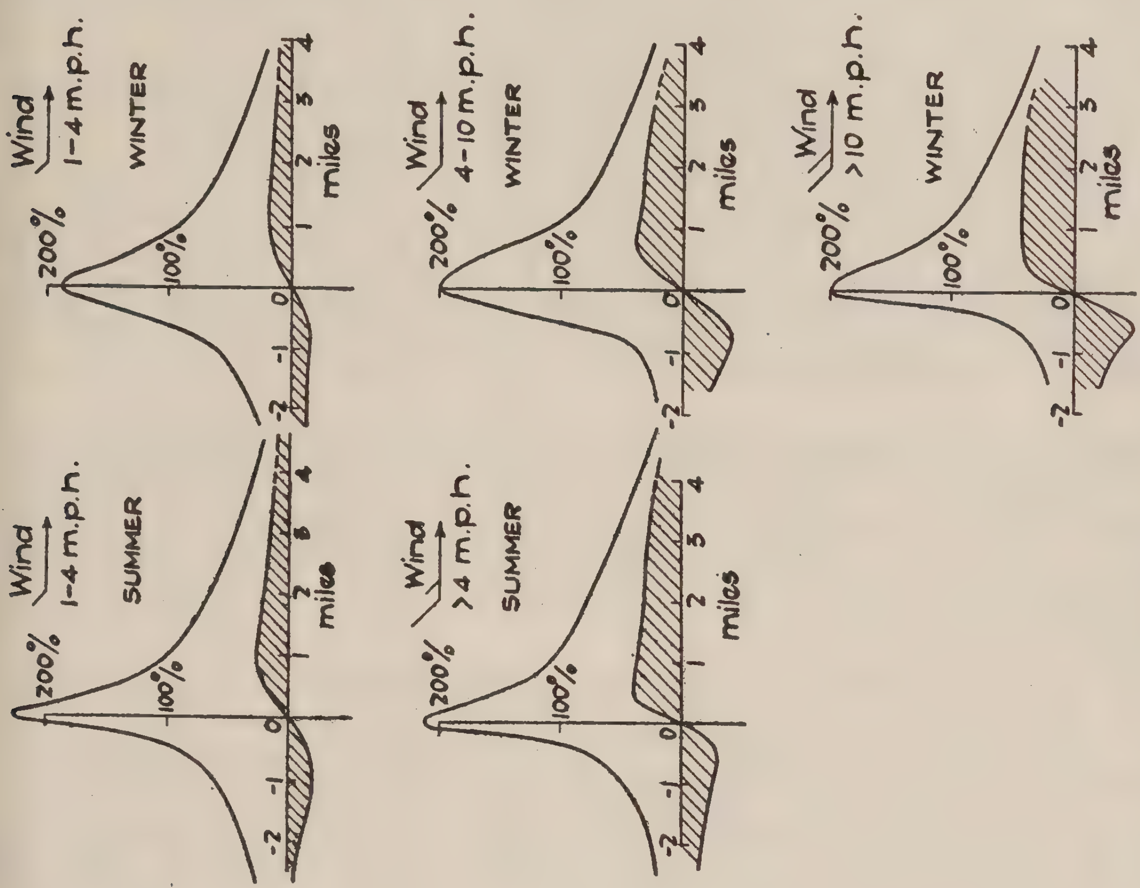


FIG. 3·492(b) SPREADING OF SULPHUR DIOXIDE UP AND DOWN WIND.

The ordinates are concentration of native pollution as percentage of the concentration in Central Leicester. The abscissæ are distance downwind from the centre of Leicester. The shaded curves represent the net effect of wind in bringing or removing pollution.

can be got by taking the standard deviation of the ordinates throughout as 10% of the pollution in Central Leicester (10 on the vertical scale).

Now the pollution at a point acrosswind from the centre of Leicester is less

than the pollution at a point the same distance downwind, and the difference between the two is approximately the pollution brought to the downwind point from more polluted parts of the city. These differences are plotted in figures 3·492 as shaded curves. They represent the pollution brought from (or taken) elsewhere by the wind, or, from another point of view, they represent the degree of distortion from symmetry brought about by the wind.

The shaded curves are not at all accurate, but the heights of their maxima are very roughly proportional to the wind velocity; the shaded areas under them are also roughly proportional to wind velocity. Figures 3·492 show then, as well as their accuracy permits, that, although the effect of wind on distribution of pollution is small, it is roughly proportional to wind velocity. This is the only instance found during the Leicester Survey of wind having an effect proportional to its velocity; the concentration of pollution in Central Leicester, for instance, is connected with the square root of the wind velocity (Section 4·71).

On comparing the component diagrams of Fig. 3·492a and Fig. 3·492b, it is seen that the shaded areas are slightly greater for sulphur dioxide than for smoke. Also the maxima of the shaded curves are nearer the centre of Leicester for sulphur dioxide than for smoke. Both these differences are believed to depend on the same factors as the more peaked distribution of sulphur dioxide, first noticed in Section 3·41.

3·493 *Four miles downwind from Leicester*, figures 3·492 cease to be reliable. Indeed no satisfactory account has so far been given of how much native Leicester pollution is in the surface air of country districts downwind from Leicester. Yet in Section 3·44, districts 30 to 50 miles away were accused of contributing to the country pollution near Leicester. This would seem unjust unless some accusation were also made against Leicester itself. It must be admitted that after two years' observations the case against Leicester was not at all clear. This, however, was because the two country stations, 11 and 12, had been chosen specially to avoid as much as possible of Leicester's own pollution; for the purposes of Sections 3·47 to 3·49 it was necessary to examine the air before it reached Leicester.

To investigate the presence of native Leicester pollution in country air, the best place for observations would be about four miles north-east of Leicester, since the prevailing winds are south-westerly. In April, 1939, there was an opportunity to change the programme of observations and a new station was started at Scraptoft Golf Club, 4¼ miles east-north-east of Leicester (station 15 in Fig. 3·1b). The country round this station was very open, so that any pollution there in south-west or west winds would presumably have come from Leicester or beyond. To take care of pollution from beyond Leicester, station 13 was started at Thurcaston, four miles north-north-west of Leicester. Station 14 at Spinney Hill Park, one mile east of the centre of Leicester, was also started in an attempt to fill a gap in the distribution of stations. This new programme was intended to continue until March 1940, but it was cut short in December, 1939.

It is never safe to rely on the British climate, and it so happened that there were fewer south-west and west winds than usual during 1939. West winds at Scraptoft were the most polluted, but there were only nine weekdays with west winds during the summer of 1939 and four during November and December. Evidence from station 15 alone was therefore too scanty. However, there were occasions when station 13 was downwind from Leicester during 1939, and there were also occasions during January, 1937, to March, 1939, when station 12 was downwind from Leicester. Stations 12, 13, and 15 are all between 4 and 4¾ miles from the centre of Leicester, so their evidence could conveniently be grouped together.

Accordingly every weekday observation at these stations, occurring in the

months May to September or November to March, was examined. By subtracting the lowest observation anywhere on that day a daily estimate was made of the native pollution reaching stations 12, 13, and 15. Sometimes the station downwind had the lowest observation, in which case the next lowest observation was subtracted from it, giving a negative result. Although a negative concentration of pollution is impossible, there are advantages, connected with theory of sampling, in allowing these estimates of native pollution to include negative numbers. Estimates were then sorted, irrespective of station, into summer and winter and into light, moderate, and fresh winds as before (Section 3·42); and also into three wind directional groups—(a) downwind, when the mean wind direction for the day was within the octant opposite to any station, (b) adjacent winds, when the mean wind direction was in one of the two adjacent octants, and (c) other winds, when the mean wind direction was in one of the five remaining octants. Means and standard errors of the various groups are given in Table 3·493.

On the whole the conclusions from Table 3·493 are clear. During light winds in summer there is some doubt, and no evidence is available for light winds in winter, but in all other circumstances there is significantly more pollution four miles downwind than four miles in other directions from Leicester. If the pollution in Central Leicester is 100 units, the pollution four miles downwind includes 3 to 34 units from Leicester itself, with an average of 15 units; also 0 to 15 units from other sources than Leicester, with an average of 7 units.

TABLE 3·493. *Pollution from Leicester in Surrounding Country*

The means in the table are estimates of native Leicester pollution about 4 miles from the centre of Leicester, when the wind blows directly from Leicester, or from elsewhere. Estimates were based on observations at Stations 12, 13 and 15, except in the section marked (*) for which there were no observations at Station 13 or 15. Results are expressed as percentage of the pollution in Central Leicester.

	Smoke		Sulphur Dioxide	
	No. of days	Mean ± S.E. of mean	No. of days	Mean ± S.E. of mean
SUMMER				
Light winds 1 to 4 m.p.h.				
		% %		% %
Downwind	14	18 ± 4	12	18 ± 6
Adjacent winds	36	21 ± 3	35	8 ± 3
Other winds	103	15 ± 2	98	10 ± 2
Moderate winds > 4 m.p.h.				
Downwind	30	21 ± 3	25	18 ± 4
Adjacent winds	67	17 ± 1	63	16 ± 2
Other winds	176	11 ± 1	161	7 ± 2
WINTER				
(Light winds 1 to 4 m.p.h.:—insufficient data available)				
Moderate winds 4 to 10 m.p.h.				
Downwind	16	24 ± 5	16	14 ± 4
Adjacent winds	40	15 ± 2	38	7 ± 3
Other winds	96	8 ± 1	89	3 ± 2
*Fresh winds 10 m.p.h.**				
Downwind	7	39 ± 6	7	27 ± 10
Adjacent winds	25	17 ± 3	22	7 ± 4
Other winds	62	5 ± 2	62	0 ± 2

On the same scale country pollution amounts to an average of 30% in westerly winds, and 20% in easterly winds. Assuming in accordance with the conclusions of Section 3·47 that in westerly winds 10% is the contribution of the Birmingham industrial area, the following estimates emerge:

Origin of pollution in surface air at a point 4 miles east of Leicester, in west winds

Pollution from Leicester	=15 arbitrary units
Pollution from Birmingham district (30 to 45 miles upwind)	=10 ,, ,,
Completely exotic and very local pollution	=20 ,, ,,

The population of Leicester is about $\frac{1}{4}$ million, and the population in an area 30 to 45 miles W-WSW of Leicester, which includes Birmingham and Wolverhampton, is about 2 millions. Thus 8 times the population of Leicester has $\frac{2}{3}$rds the effect when 10 times as far removed. It seems as if the law of dilution of pollution with distance is more nearly a linear law than a square law. This is interesting, because very simple considerations point to a square law if pollution can diffuse upwards as well as sideways, but to a linear law if pollution diffuses sideways only or upwards only. This matter is discussed further in Section 5·12.

3·5 Distribution of Emission

Hitherto discussion in this chapter has been confined entirely to the distribution of pollution. If P is a measure of deposited pollution or of suspended pollution, the chief question has been how P varies from place to place in various circumstances. P is the pollution which is observed at any place by any of the methods discussed in Chapter 2.

A quite different point of view emerges by considering E, the pollution emitted within a given area in a given time. Clearly E will have fairly regular diurnal and seasonal variations, but will vary little from day to day, except at weekends. Unlike P, however, E will be independent of wind and turbulence. E will always be expressible as *mass/area* × *time*, e.g. tons per square mile per month, and there is danger of confusing E with deposited matter for that reason. The confusion may be reduced by considering a simple example. Suppose there is an industrial island of exactly one square mile, so far removed from other inhabited places that their effect is negligible. Suppose the chimneys of this island emit E tons of ash in an average month. Then the ash emitted is E tons per square mile per month. Some of the ash will be blown out to sea, but an amount P tons will be deposited on the island per month. The ash deposited will therefore be P tons per square mile per month. It is evident that P will be less than E. In fact if $p_1\ p_2\ p_3 \ldots\ldots\ldots$ tons are deposited in the various square miles of sea surrounding the island,

$$E = P + p_1 + p_2 + p_3 + \ldots\ldots\ldots$$

Thus in the island itself, emitted pollution exceeds deposited pollution, but on the sea nearby the converse is true. Now E is a quantity of great practical importance, but it is very difficult to measure directly on a large scale. In the simple case of the island, the easiest way to estimate E would be to measure P, p_1, p_2, p_3, etc., by the methods of Chapter 2 and add them all together. In the more complicated case of an inland town such a straightforward method will not serve, but it is still possible to estimate some of the properties of E from a knowledge of P.

In considering the Leicester measurements, it is evident that little could be learned of the emission of depositable matter, because four deposit gauges analysed monthly, do not give sufficient information about P. The hourly observations of suspended impurity at four stations are open to a similar objection. There remain the daily observations at 12 stations of daily mean

smoke and sulphur dioxide concentrations. These have shown themselves sufficient to indicate, in a very general form, the distribution of smoke and sulphur dioxide in Leicester; they may also be made to indicate the approximate distribution of emission in Leicester, and the seasonal and weekly variation of emission, but the results will be in arbitrary units. Without knowledge of the vertical and lateral spread of smoke and sulphur dioxide, it is impossible to express results in absolute units.

Using observations of P, there are three ways of examining E.

(1) *In perfect calms* the connection between P and E will be particularly close, and in the case of deposited matter P and E should be identical. One difficulty is that calm weather seldom lasts long enough to give a suitable estimate of P; another is that even in what we call calm weather appreciable air-exchange occurs. The distribution of suspended matter in calms will be most similar to the distribution of emission when there is considerable atmospheric turbulence, i.e. when smoke diffuses away vertically before it can drift along the ground.

(2) *In steady winds* the suburbs in a direction at right angles to the wind from the centre of a symmetrical town will be receiving pollution from suburbs similar to themselves, provided that the wind is not too strong. Evidently figures 3·48, representing the local pollution under different conditions, may be used to provide a second estimate of the distribution of emission.

(3) *Mean distribution of P.* It was pointed out in Section 3·46 that a surprisingly small empirical correction was needed to convert a map of mean distribution to a map of relative distribution in calms. This result applied to smoke and sulphur dioxide. (The corresponding correction for deposited matter would probably be smaller still, but it cannot be estimated from existing data.) Hence it may be convenient to convert an observed mean distribution of P to a distribution in calms, from which the distribution of E may be estimated.

3·51 *Estimates of Emission by Methods* 1 *and* 2.

The distribution of smoke and sulphur dioxide in calms, shown in figures 3·46, is very closely connected with the distribution of emission. In a perfect calm the only means of escape for pollution are settlement and upward diffusion, both of which would be expected to be proportional to concentration. To a first approximation, a small amount of lateral diffusion would not change the concentrations anywhere, and therefore

$$P = kE$$

where k is a constant depending on settlement and diffusion. Although k will vary from one calm day to another, it will not affect relative concentrations of pollution in different districts. When every concentration is expressed as a fraction of the concentration in Central Leicester for that day, any number of days' records may be averaged.

The above equation is not strictly true for the Leicester results because (a) absolute calms for periods of 24 hours did not occur (daily mean wind velocities of $\frac{3}{4}$ m.p.h. or less were therefore rated as calms, so that lateral diffusion may have been considerable); (b) there are real variations in climate over areas the size of Leicester (a familiar example is the tendency of cold, smoky air to remain in valleys when the wind is light); and (c) the air contained pollution emitted before the calm began. A correction may be made for (c) by subtracting the minimum number on each map from all the other numbers. Even after making this correction, the estimate of distribution of E will be too uniform, because of the lateral diffusion implied by (a) and (b).

Method 2 depends on the assumptions that Leicester is symmetrical, and also that the local pollution at any point, as given in figures 3·48, originated not more than one or two miles upwind. The suburbs in a direction from Leicester at right angles to the wind will then receive pollution from suburbs similar

to themselves, provided the wind is not too strong. If from figures 3·48 stations are picked out which are acrosswind from Leicester for each win direction, and if their average pollution is taken over all wind directions, th result will be an estimate of suburban emission on an arbitrary scale. Whe this is divided by the appropriate figures for Station 1, it provides an estimat of suburban emission compared with the emission at the centre. Stations 5, 6 7, 8, 9, 10 are regarded as suburban stations, their mean distance from Station being 2·3 miles. The inner Stations 2, 3, 4, whose mean distance from Station is 1·2 miles, may be treated similarly.

In Table 3·51 results for different wind speeds are given separately for smok and sulphur dioxide. The results by methods 1 and 3 have been included.

TABLE 3·51. *Estimates, by Methods* 1, 2 and 3, *of the relative amount of pollutio emitted at the inner and suburban groups of stations for every* 100 *unit emitted near Station* 1.

Inner Group: Stations 2, 3 and 4, their average distance from Station 1 being 1·2 miles.
Suburban Group: Stations 5, 6, 7, 8, 9 and 10, their average distance from Station 1 bein 2·3 miles.

	SUMMER				WINTER				
	Method 1	Method 2		Method 3	Method 1	Method 2			Methoc 3
Wind Velocity, m.p.h.	0	1-4	>4	—	0	1-4	5-10	>10	—
	SMOKE								
Inner	53	56	50	59	70	65	58	48	64
Suburban	18	23	18	19	26	23	18	10	27
	SULPHUR DIOXIDE								
Inner	34	25	25	29 (38)	42	40	33	30	33 (40)
Suburban	23	15	16	16 (19)	17	16	10	8	18 (18)

Note: Daily observations of smoke and sulphur dioxide were used for estimating all th above numbers except those in brackets, which were derived from lead peroxid results.

By method 2, estimates in Table 3·51 are generally lower in stronger wind than in light winds. In stronger winds a station acrosswind from the centre o Leicester apparently receives a high proportion of pollution which has originate in cleaner districts, and this is an indication that even estimates in 1 to 4 m.p.h winds by method 2 may be low. Estimates by method 1, on the other hand, ar likely to be high because of diffusion from the centre to the suburbs. Fo sulphur dioxide in summer method 1 gives 50% higher estimates than method 2 but the two methods are otherwise in good agreement. The figures for winds o 0 and 1 to 4 m.p.h. in Table 3·51 are therefore the most probable values o emitted pollution in inner and suburban Leicester, the emission in the centr being taken as 100.

3·52 *Estimates of Emission by Method* 3.

If the mean distribution of smoke or sulphur dioxide is modified by multiply ing by 0·9 the values at the two country stations, 11 and 12, the result is ver similar to the distribution on calm weekdays. One point of difference is tha the absolute values of pollution, derived from the mean distribution, are muc lower than the values usually to be observed in calms; this is not importan

since this chapter is mostly concerned with relative distribution. The other point of difference is that the mean curves are influenced by the asymmetry of wind direction, westerly winds being from two to four times as common as easterly winds. This point is brought out on comparing, for individual suburban stations, the mean concentration of pollution relative to Central Leicester and the concentration in calms. For the easterly stations (5, 9, 10) the mean concentration is respectively 14%, 1%, and 21% higher (relatively) than the concentration in calms; for the westerly stations (6, 7, 8) the figures are 21% lower, 7% higher, and 23% lower. (The distinction between easterly and westerly is the same as that in Section 3·47.) However, this point of difference between the modified mean distribution and the distribution in calms is avoided by averaging groups of stations which are regularly spaced at a uniform distance from the centre of the town. Stations 2, 3 and 4 form one such group, and Stations 5 to 10 another.

Method 3 then consists of multiplying the mean readings at Stations 11 and 12 by 0·9, converting a mean distribution to a relative distribution in calms; then subtracting the lowest reading from all the other readings, as for method 1.

Method 3 does not, of course, provide a completely independent check on methods 1 and 2, because it is derived in part from method 1. Appropriate results by method 3 are inserted in Table 3·51, so that they may be compared with results by the other two methods. Method 3 appears rather to accentuate the difference between the distributions of emission of smoke and sulphur dioxide, but it is interesting to note that the results by method 3 for sulphur dioxide with the lead peroxide method are in good agreement with the results by methods 1 and 2, which are with the volumetric method.

The full set of results by method 3 which have been obtained from records of the Leicester Survey is given in Table 3·52. Not only is it possible to use results for sulphur dioxide by the lead peroxide method, but in addition special use may be made of Sunday readings by the combined smoke and volumetric sulphur apparatus. There is no significant difference in distribution between the Sunday and weekday emission of sulphur dioxide; but for smoke every figure for Sundays is higher than the corresponding figure for weekdays. Moreover, the ratio of suburban to inner smoke emission can be seen by inspection to be greater for Sundays than for weekdays. Presumably the population of Leicester

TABLE 3·52. *Estimates, by Method 3, of the relative amount of pollution emitted at the inner and suburban groups of stations for every* 100 *units emitted near Station* 1.

Inner Group: Stations 2, 3 and 4, their average distance from Station 1 being 1·2 miles.
Suburban Group: Stations 5, 6, 7, 8, 9 and 10, their average distance from Station 1 being 2·3 miles.

	SUMMER		WINTER	
	Weekdays	Sundays	Weekdays	Sundays
	SMOKE			
Inner	59	61	64	73
Suburban	19	23	27	34
	SO_2 (Volumetric method)			
Inner	29	28	33	32
Suburban	16	14	14	18
	SO_2 (Lead Peroxide method)			
Inner	38	—	40	—
Suburban	19	—	18	—

moves outwards towards the suburbs at week-ends; smoke production appears to move with the population but production of sulphur dioxide apparently does not.

There is a slight logical defect in the applications of method 3 to distribution of emission on Sundays. The empirical correction is made to convert mean distribution of pollution for *all days* into distribution during calms on *weekdays*. Clearly the same correction cannot be applied strictly to convert mean distribution of pollution for *Sundays* into distribution during calms on *Sundays*. However, because the differences in estimates of weekday and Sunday emission in Table 3·52 are small, this defect is unimportant.

3·53 *Human Habits.*

By using Tables 3·51 and 3·52 in conjunction with estimates of the periodic variations in emission of pollution, it is possible to form an estimate of the relative smoke and sulphur emissions of the population in different circumstances.

In winter, much fuel is used for warming the population. From Fig. 4·71 it can be calculated that in Central Leicester, under similar conditions of wind and turbulence, 2·47 times as much smoke is present in the five winter months as in the five summer months, and 2·39 times as much sulphur dioxide. Some of this pollution is exotic; correcting for exotic pollution as in methods 1 and 3, it can be shown that both for smoke and sulphur dioxide about 3·2 times as much pollution is emitted in winter as in summer. This result, when used in combination with the information in Tables 3·51, yields part (a) of Table 3·53 below.

Table 3·53(a) has been calculated from the mean of the estimates of emission for wind velocities 0 and 1 to 4 (columns 1, 2 and 5, 6 in Table 3·51). The winter

TABLE 3·53 (a) AND (b) *Seasonal and weekly changes in emission of smoke and sulphur dioxide*

	SUMMER		WINTER	
	Weekdays	Sundays	Weekdays	Sundays
	(a) By methods 1 and 2			
	SMOKE			
Station 1	100*		278	
Inner	54		187	
Suburban	20		69	
	SULPHUR DIOXIDE			
Station 1	100*		271	
Inner	30		111	
Suburban	19		44	
	(b) By method 3			
	SMOKE			
Station 1	100*	57	304	206
Inner	59	35	194	150
Suburban	19	13	82	70
	SULPHUR DIOXIDE			
Station 1	100*	56	300	196
Inner	29	16	99	63
Suburban	16	8	57	35

* The units are arbitrary, the average emission at Station 1 on summer weekdays being taken as 100.

values have been calculated to make the winter mean of Stations 1, 2, 3, 4 equal to 3·2 times the summer mean. The greatest seasonal variation in emission of both smoke and sulphur dioxide is seen to occur in the inner suburbs, where the greatest ratio of population density to density of industrial undertakings is likely to be found. This is to be expected, since factories use considerable quantities of fuel for power all the year round, and also since methods of domestic heating are usually far less efficient than methods of heating offices and factories.

Table 3·53(b) has been calculated in a similar way to Table 3·53(a), by using the weekly cycles from Table 4·311 in conjunction with Table 3·52. Table 4·311 indicates that in summer about 0·58 times as much smoke is emitted in Central Leicester on Sundays as on weekdays, and about 0·55 times as much sulphur dioxide. In winter, the figures are 0·74 for smoke and 0·64 for sulphur dioxide. Taking the average emission on summer weekdays as 100, and using Table 3·52, Table 3·53(b) can be drawn up.

It should be noted that Tables 3·53 (a) and (b) are in the same units, average summer emission near Station 1 on weekdays being taken as 100. The only difference is that Table 3·53(a) uses methods 1 and 2 for estimates of relative emission, whereas Table 3·53(b) uses method 3. The reduction of smoke emission on Sundays compared with weekdays in the inner and outer suburbs is not very great, possibly because of Sunday cooking. The corresponding reduction of sulphur dioxide appears to be considerable, however, especially in summer. This might be a fictitious result, brought about by the disturbing influence of atmospheric ammonia, but it suggests that much of the sulphur dioxide in the inner and outer suburbs is due to industrial activity.

Even on weekdays, of course, the population does not spend a particularly large proportion of its time at work. It is interesting to consider how much pollution is made by the population at work. On a rough analysis, taking the year as a whole, the population spends 26% of its time on work, 41% on leisure, and 33% on sleep. The distribution of emission on Sundays, given in Table 3·53(b), is roughly representative of the population 67% at leisure and 33% at sleep. The amount of work done on Sundays, and the differences in occupation of Sunday and weekday leisure, will be ignored here. It will be assumed that no heating is required for bedrooms, and no pollution is produced by the population at sleep. The contribution of the people at leisure during an average day is therefore 41/67 of the emission on Sundays. Subtracting 41/67 of the Sunday emission from the emission on all days yields the results shown in Table 3·53 (c).

It will be noted that only in the outer suburbs in winter is there more pollution emitted during leisure than there is during work. The emission of sulphur

TABLE 3·53(c) *Emission of smoke and sulphur dioxide during work and leisure on weekdays on the basis of average daily emission at Station* 1 *in summer* = 100.

	Summer		Winter	
	Work	Leisure	Work	Leisure
		Smoke		
Station 1	63	37	144	108
Inner	36	23	82	79
Suburban	11	8	31	37
		Sulphur Dioxide		
Station 1	63	37	126	92
Inner	19	10	43	29
Suburban	11	5	14	17

dioxide may be taken as an index of the amount of coal burnt. The table then shows that the population in the inner and outer suburbs, whether at work or leisure, makes about twice as much smoke in proportion to the coal burnt as the population near Station 1. In any drive for the reduction of smoke, therefore, special attention should be paid to the smoke which is produced in the inner and outer suburbs.

3·6 Distribution of Combustion Efficiency

Information about efficiency of combustion can be obtained from the Leicester Survey, if it can be assumed that the emission of sulphur dioxide is proportional to the weight of coal burned.

The sulphur content of coal may vary from about 1% to 4%, but the mean sulphur content of the coal burned in a district of 100 or more acres is probably very nearly constant for the districts of a given town. There is a tendency for gasworks and some power stations to burn the more sulphur-free coals, and there may be other differences between the mean sulphur content of domestic and industrial coals. Possibly some variation of the mean sulphur content with time might occur, but variations with time are not considered here. The greater part of the sulphur in coal emerges from the chimney as sulphur dioxide, the rest being associated with the ash, and the proportion of sulphur emitted as sulphur dioxide depends to some extent on how it is combined with other elements in the coal. It is therefore only approximately true to assume that the emission of sulphur dioxide is proportional to the weight of coal burnt.

Table 3·6(a) contains the mean ratio of smoke to sulphur dioxide, as *emitted* in different zones of Leicester. It is derived from Table 3·53(a), which may be deemed the best available estimate, from the Leicester Survey, of emission of smoke and sulphur dioxide. The units are arbitrary, being chosen so that the average ratio for Station 1 in summer is 1·0. Table 3·6(b) is similarly derived from Table 3·53(b); it contains estimates for Sundays, but is more precariously based (see Section 3·52). Table 3·6(c) is derived directly from the mean distributions of pollution in figures 3·41 and 3·411; it therefore contains the mean ratios of smoke to sulphur dioxide *concentrations*.

According to the second paragraph of the present section, then, the figures in Tables 3·6 (a) and (b) are approximate estimates, on an arbitrary scale, of

Table 3·6 (a), (b) and (c) *Mean smoke-sulphur ratio.*

	Summer		Winter	
	Weekdays	Sundays	Weekdays	Sundays
	(a) Smoke-sulphur *emission* ratio, from Table 3·53(a)			
Station 1	1·0*		1·0	
Inner	1·8		1·7	
Suburban	1·1		1·6	
	(b) Smoke-sulphur *emission* ratio, from Table 3·53(b)			
Station 1	1·0*	1·0	1·2	1·2
Inner	2·0	2·2	2·2	2·7
Suburban	1·2	1·8	2·2	2·2
	(c) Smoke-sulphur *pollution* ratio, from Figs. 3·41 and 3·411			
Station 1	1·0*	1·1	1·1	1·1
Inner	1·8	1·8	1·8	2·2
Suburban	1·2	1·5	1·8	2·2

* The units are arbitrary, the average ratio at Station 1 in summer being taken as 1·0.

the weight of smoke emitted per ton of coal burned. The outstanding feature of the table is that least smoke is produced per ton of coal burned in the neighbourhood of Station 1—i.e., the centre of Leicester. Evidently most of the big shops and office buildings in this neighbourhood employ central heating and other relatively smokeless methods; there are few private dwellings here, and probably but little coal is burned in open grates.

In the inner and outer suburbs similar weights of smoke are produced for each ton of coal burned, except that little smoke is produced in the outer suburbs on summer weekdays. On the whole, the inner suburbs are the worst smoke-makers, although they include the power station and other factories where fuel economy is practised and the minimum of smoke is produced. Evidently some of the coal is burned extremely smokily in the inner suburbs; there is little doubt that this occurs in very many old houses, where coal is burned inefficiently for cooking and water heating. The most smoke per ton of coal burned is emitted on Sundays, when the efficiency of industrial consumption is not felt. Although on Sundays less smoke is present than on weekdays, still less coal proportionally has been burned to produce it.

After emission from the chimneys, smoke behaves rather similarly to sulphur dioxide. Smoke particles appear to have an average diameter of about 0·1 micron, and particles 100 times as big as this fall at a negligible rate under gravity. In perfectly still air, smoke would diffuse much more slowly than gases, but in the free atmosphere diffusion is the result of turbulence, and particles are diffused at the same rate as gases. The action of rain may be different for smoke and sulphur dioxide, and there is the possibility that sulphur dioxide may combine with atmospheric ammonia; but, as much of the pollution entering the instruments at Leicester could only have been in existence for less than an hour, these considerations are probably of secondary importance. Thus if smoke and sulphur dioxide are emitted at the chimneys in a given ratio, they will probably be received at the instruments in very nearly the same ratio.

It is to be expected also, then, that Table 3·6(c) will approximately represent the distribution of combustion efficiency in Leicester. That it does so is evident from its similarity to Tables 3·6 (a) and (b). The practical result is that the ratio of smoke to sulphur dioxide in the atmosphere can be used as an approximate measure of the mass of smoke made per ton of coal burned. Hence, a watch can be kept on progress in smoke abatement by observing atmospheric sulphur dioxide in addition to atmospheric smoke. A reduction in smoke, unaccompanied by a reduction in sulphur dioxide, is a strong indication that improved methods of coal burning have been introduced. The smoke-sulphur ratio should be used systematically in the investigation of atmospheric pollution.

3·7 Effect of a Smokeless Zone

In "Smokeless Air" for Spring, 1940, the Journal of the National Smoke Abatement Society, there is reference to a proposed smokeless zone in the centre of Manchester. Briefly it is proposed that an area of 104 acres or about one-sixth of a square mile should be made nearly smokeless by suitable alterations in the fuel consumed by 3,901 open grates. The area in question is chiefly commercial, and is already relatively free from open fires. This very interesting proposal naturally raises the question, What would be the effect of eliminating all smoky fires in a specified area near the centre of a large town? An approximate answer should be possible from an examination of the results set out in this chapter.

The chief difficulty is that no observations were made in Leicester of the distribution of smoking domestic chimneys, at the same time as the measurements of smoke concentration were being made. This means that there is no definite connecting link available between distribution of sources and dis-

tribution of pollution. However, in absolutely calm weather no smoke could enter a smokeless area, so the distribution of smoke in smokeless zones is known in absolute calms. Now if the difference between the distribution in absolute calms and in an average wind were known for Leicester, it should be possible to calculate the average distribution in a smokeless area. The average distribution of smoke in Leicester in winds is known, but the distribution in absolute calms has not been observed, and would be extremely difficult to observe, although the average distribution in conditions approximating to calm is known.

The data are therefore inadequate for the strict calculation to be made, but, neglecting the difference between approximate and absolute calms, the probable distribution in a smokeless area was calculated. It was found that a smokeless zone of $\frac{1}{6}$ sq. mile within a large smoky area would have an average reduction of smoke at its centre of 11%, and a zone of 1 sq. mile would have an average reduction at its centre of 58%. Rather smaller reductions would occur if the smokeless zone were in a limited smoky area the size of Leicester. It is probable also that, because of the difference between approximate and absolute calms, these estimates show in any case too large a reduction.

3·71 *Observations in a Smokeless Zone.*

The considerations of the previous section are based on an assumed relationship between the distribution of emission and the distribution of smoke in calm weather. Also they deal with mean conditions, and not with specific wind directions, whereas in any particular wind the cleanest part of a smokeless zone would not be at the centre but at the leeward edge. It would evidently be better to make observations in a real smokeless zone. Now smokeless zones already exist in all big towns, in the form of public parks. Here little pollution is usually emitted, except for smoke from burning leaves, so that parks are very nearly ideal smokeless zones.

On 10 afternoons in March, 1943, measurements were made of the smoke concentration in Hyde Park and Kensington Gardens, London. Smoke stains were obtained by drawing 2 litres of air through filter papers with hand pumps, and were read by comparison with the Owens' Scale of shades. The same type of filter paper was used as in the Automatic Filter, so that readings were comparable, after correcting for the different diameter of stain. Observations were made at 13 points in and around the smokeless area, between 13.30 and 17.30 h. B.S.T., when the regular diurnal variation of smoke is small. Errors due to uniform increase or decrease of pollution were avoided by making two observations at each point, at equal times before and after 15.30 h. B.S.T. The investigation was confined to wind directions which were longitudinal or transverse to the park. Intermediate wind directions were avoided.

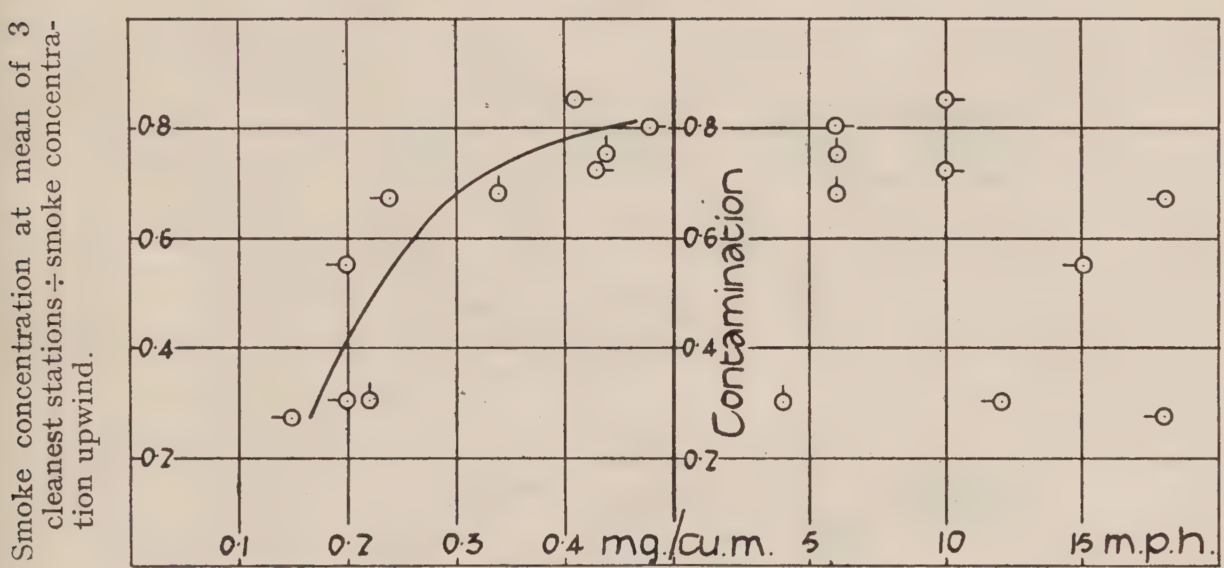
Let the ratio of smoke concentration at the cleanest part of the park to smoke concentration upwind be termed the contamination of the park. The contamination varied very considerably during the 10 days of observation, from 0·27 to 0·85, where the mean of the three cleanest stations is taken to represent the cleanest part of the park. Fig. 3·71 (a) helps to show why this great variability occurred.

In the right-hand portion there is evidently little or no connection between contamination and wind velocity, but on the left there is a well marked dependence on mean smoke concentration. When conditions are such that smoke concentrations are everywhere low, the proportional contamination inside Hyde Park is exceptionally low; hence when there is little smoky pollution in London as a whole there is much less still in Hyde Park, but when London is dirty Hyde Park is nearly as dirty as the rest of London.

Now the conditions which make for low concentrations of smoke will be shown to be strong turbulent mixing, and it follows that the proportional

contamination of smokeless areas is least when mixing is strongest. Here is the true explanation, surely, of why the contamination of a smokeless area varies so much from day to day. On a turbulent day, an unusually large proportion of the suspended pollution in urban districts is of extremely local origin, because pollution from more distant sources rapidly diffuses upwards, to be swept away by the wind. It follows that in a smokeless district there is an unusually large proportion of clean air on a turbulent day.

The distribution of smoke in Hyde Park is strongly dependent on the wind direction. During the 10 sets of observations, the wind was 4 times between SW and W, 3 times between NW and N, and 3 times between NE and E. There were no winds between SE and S. Thus on seven days there were easterly or westerly winds blowing along the length of the park, and these were treated as one group (longitudinal). The remaining three days of northerly winds were also treated as a group (transverse). Fig. 3·71(b) shows the mean distribution of smoke in transverse and longitudinal winds, the concentrations being expressed as ratio to the mean smoke concentration upwind from the park. Stations which are symmetrically placed about the axis of symmetry were averaged together. Thus the symmetrical nature of the diagrams is an assumption, not an observed fact; indeed in practice each individual day's observations were usually slightly asymmetrical because the wind direction



Mean smoke concentration upwind. Wind velocity at 33 ft.

FIG. 3·71(a) CONTAMINATION OF HYDE PARK BY SMOKE FROM UPWIND.

Note: Tails attached to the circles indicate wind direction.

did not exactly coincide with the major or minor axis of the park. The estimated standard error of the numbers in the upper diagram varied between 0·03 and 0·14, and in the middle diagram between 0·02 and 0·09; but the variance must be attributed to the effect of different degrees of turbulence, as well as instrumental and sampling errors.

Finally, the bottom diagram of Fig. 3·71(b) is an estimate of the average distribution of smoke in Hyde Park, derived from the other two diagrams by allowing for the average relative wind frequency at Greenwich. No allowance is made for calms, but these are comparatively rare, occurring about once in twenty observations. The mean pollution in London districts during the 10 afternoons when measurements were made in Hyde Park was so close to the winter mean that no correction is necessary for turbulence. The diagram therefore represents the mean pollution that would be observed at different parts of the Park on winter afternoons, if the average were taken over a long period.

Since this particular smokeless area is approximately one square mile, the bottom diagram of Fig. 3·71(b) may be compared with the conclusions of 3·7, except that there is a difference in shape of the smokeless area. It was estimated in Section 3·7 that the mean improvement at the centre would be 58%, whereas in Hyde Park it was only about 27%. It seems probable that Section 3·7 is at fault, too little pollution being assumed in calms at the centre of the smokeless zone.

From the results of Section 3·43 it was concluded that much insoluble deposited matter falls to ground near the chimney from which it is emitted. It is to be expected, therefore, that Hyde Park is less contaminated by deposited

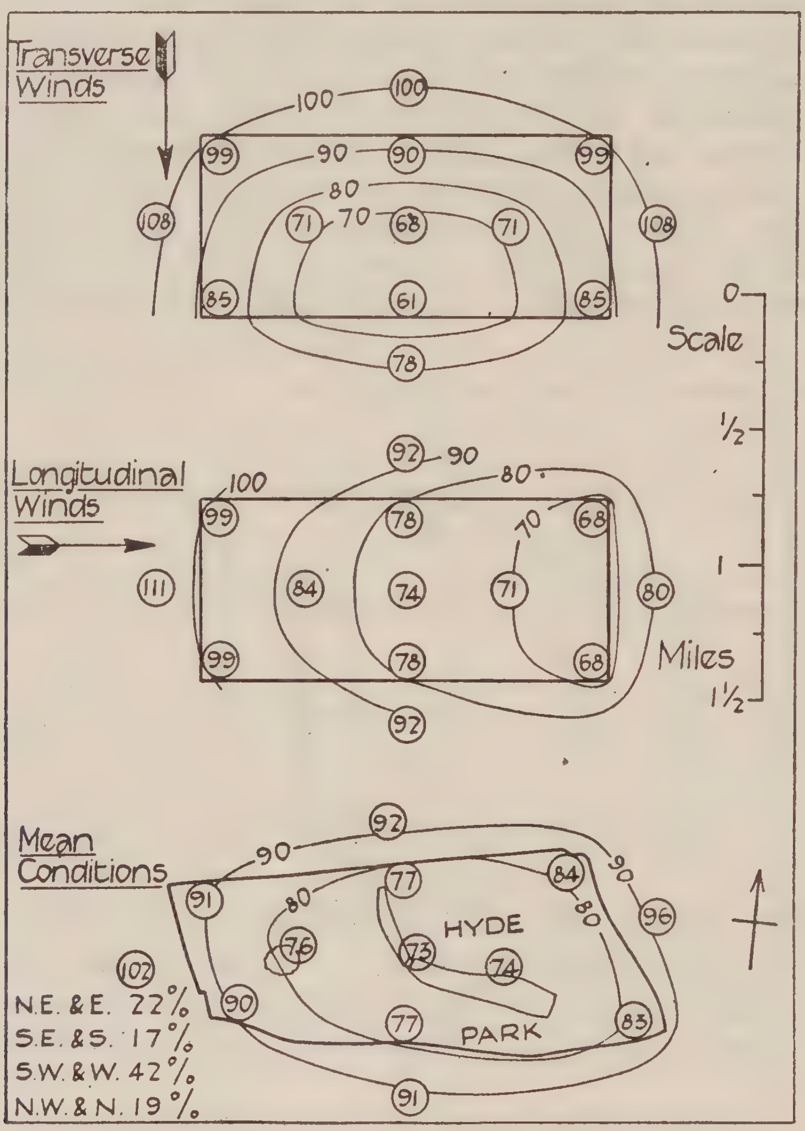


FIG. 3·71(b) SMOKE IN HYDE PARK.
Expressed as percentage of smoke concentration upwind from the Park.

matter than by suspended matter. An investigation of this question by Mr. J. H. Coste is described in Appendix 6·2.

The experiments in Hyde Park show how much a smokeless area suffers from the smoke from neighbouring areas. The average reduction in pollution to be expected at the centre of a square mile free from smoke emission is 25% to 30%, but in different weather conditions the reduction may be anything from 15% to 75%. There is also appreciably less pollution in the adjoining districts. Reductions of less than 50% to 75% would probably be insufficient to impress the average citizen. The introduction of small smokeless zones is therefore unlikely to bring about a great increase in the popular demand for purer air, unless the improvements are measured accurately and the results made public.

The same difficulty will probably beset any other partial measures, unless they provide a sharp contrast in smokiness between two contiguous areas. Hence it is imperative that all special measures against pollution should be accompanied by systematic observations, for the information both of the authorities and the general public.

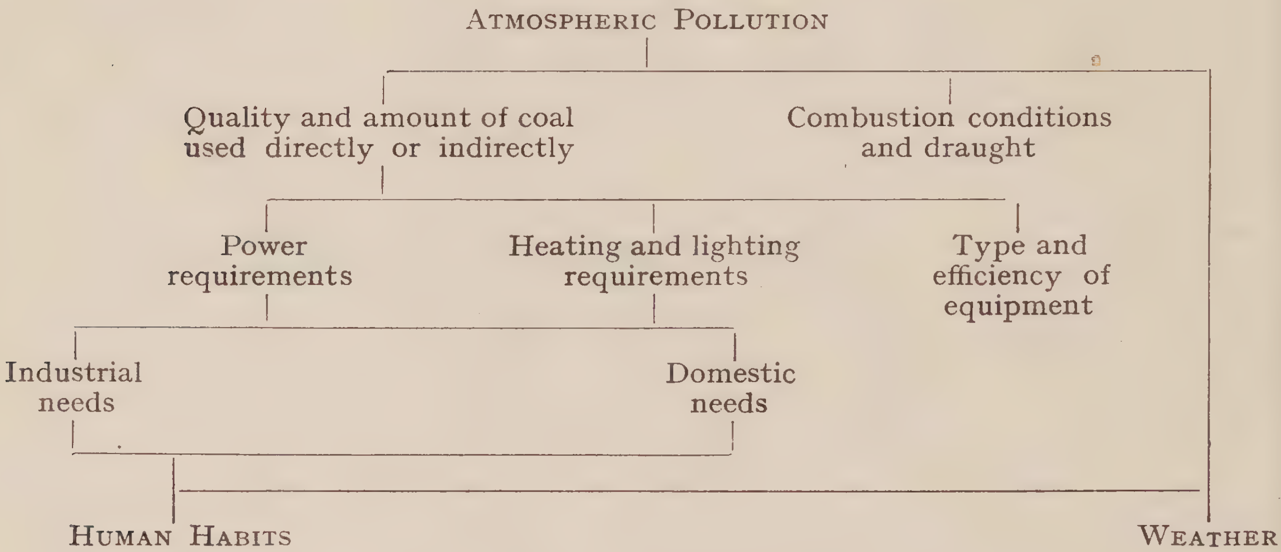
4·0. VARIATION OF POLLUTION WITH TIME

4·1 Introduction

Two of the most striking characteristics of atmospheric pollution are its variation from place to place and its variation at any one place from time to time. The distribution of pollution in and around Leicester was discussed in Chapter 3. The present chapter deals with the variations of pollution with time which were observed in Leicester.

Pollution changes with the same bewildering rapidity as weather; indeed it will be shown to have a close connection with weather. It also varies with the amount of coal burned in houses and factories. The coal burned in houses, offices, and even industrial works is partly dependent on the outdoor temperature, because in cold weather more coal is needed for providing heat. The amount of coal used for making gas or electricity varies according to the many purposes for which the gas and electricity are required; since these purposes include the heating of buildings, there will again be appreciable dependence on weather. On the other hand, the coal used for cooking, for providing hot water, and for power to drive machinery is far less dependent on temperature and weather generally. Table 4·1 summarizes the situation, and it applies to all forms of atmospheric pollution which are derived from coal. The diagram should be read downwards, and every line represents the words "depends on."

Table 4·1



With two exceptions, every item in the above diagram must vary in one way or another with time. The exceptions are combustion conditions and draught, and type and efficiency of equipment. Even these items will vary gradually, but the variations in the three years 1937-9 are unlikely to have made a noticeable difference to atmospheric pollution at Leicester, and may be neglected.

4·11 *Types of Variation*

The remaining items in Table 4·1 may vary irregularly, or periodically, or in both ways together. Periodic variations are specified by the time required for a full cycle. The commonest periods are *yearly*, such as the seasonal variation of weather, and *daily*, such as the 24-hourly variation of temperature due to the rising and setting of the sun. In addition a *weekly* period occurs in the

use of coal, because of different human habits at week-ends. The items in the diagram have been examined in turn to consider whether they are known to undergo periodic or irregular variations in the inland districts of Great Britain, and the results may be summarized as follows:

TABLE 4·11 *Variation to be expected in the circumstances affecting atmospheric pollution*

	Periodic			Irregular
	Yearly	Weekly	Daily	
Weather:				
Temperature	large	none	large	large
Humidity	small	none	large	large
Wind velocity	mod.	none	mod.	large
Wind direction	mod.	none	none	large
Turbulence	mod.	none	large	large
Rainfall	small	none	small	large
Coal used:*				
Industrial power	small	large	large	small
Domestic power	small	small	large	small
Industrial heating†	large	large	large	mod.
Domestic heating†	large	mod. or small	large	mod.

Notes: *The coal used is that for a district as a whole, so that the irregularities due to individual households and even individual factories tend to be smoothed out.
†In considering variations in amount of coal used for heating, the effects of temperature, as well as human habits, have been taken into account.

It is clear from Table 4·11 that atmospheric pollution undergoes all four types of variation, and that each type of variation is attributable to a combination of causes. The present problem is to state the amount of each type of variation suffered by each form of atmospheric pollution, and to seek out the principal factors causing each variation.

In Leicester, two forms of suspended pollution and nine forms of deposited pollution were examined. The variations in concentration of smoke and gaseous sulphur dioxide are discussed in the following sections as fully as the observations permit, but discussions of the variations of deposited matter are usually limited to three representative forms—namely, total undissolved matter, total dissolved matter, and dissolved sulphates.

The observed annual variation of the various forms of pollution will be considered first.

4·2 Yearly Cycle of Atmospheric Pollution

If the monthly average values of pollution are plotted or tabulated, they usually show the presence of a yearly cycle, although they do not lie on a smooth curve, because of irregular variations. The yearly cycle gives information about what proportion of pollution is produced for heating dwellings and work-places, but it is complicated by the yearly cycle of meteorological phenomena which affect pollution. Of the impurities investigated at Leicester, smoke has the largest range of annual variation, and insoluble deposit the smallest.

It is important to consider how many years' observations are needed to get the most useful estimate of the form and range of a yearly cycle. Table 4·11 suggests that the irregularities in monthly average values of pollution are due mainly to variable weather, but the random variations in British weather are not completely smoothed out in a 50 years' average. It would be unsatisfactory to wait 50 years for an estimate of the annual variation of pollution, and besides, in so long a period there might be considerable changes in human habits. For ordinary purposes it seems likely that about 5 years is the ideal time in which

to estimate the annual variation of pollution. The duration of the Leicester Survey was probably shorter than the ideal time for estimating yearly cycles.

4·21 *Suspended Smoke and Sulphur Dioxide*

Fig. 4·21 shows the observed yearly cycle of suspended pollution during 1937-9. The 12 stations at Leicester where suitable observations were made were grouped into four central stations (numbers 1, 2, 3, 4 in Table 3·3), six suburban stations (numbers 5, 6, 7, 8, 9 and 10) and two country stations (numbers 11 and 12). The monthly mean concentration of pollution was plotted without regard to the year, and a smooth curve was drawn as near as possible to the plotted points. Usually three different estimates of each monthly mean are available, but some estimates are missing because of instrumental difficulties and the change in programme in March, 1939. Where two or three estimates are available, they may differ considerably. The thin vertical lines in Fig. 4·21 indicate the range of variation of the monthly means.

4·211 *The irregular variation of monthly means* in Fig. 4·21 is similar, proportionally, for all three groups of stations. For the central stations the standard deviation of a monthly mean, or more strictly the square root of its variance, is about 20% of the annual mean; for the suburban stations it is 25%, and for the country stations 33%. In the more rural districts a greater proportion of the pollution is exotic, and exotic pollution evidently undergoes even greater irregular variations than local pollution. In addition, there are variations in each suburban district due to changes in wind direction. These variations do not appear in Fig. 4·21 because symmetrical groups of stations were used, but they may be examined in Figs. 3·48, where each station is treated separately. Apart from these differences it seems probable that the causes of irregular variation are the same in other districts as in Central Leicester. The causes of irregular variation in Central Leicester are considered in Section 4·7. There are indications in Fig. 4·21 that the irregular variation of monthly means is less, proportionally, in summer than in winter. This will be discussed in Section 4·711.

The smooth curves of Fig. 4·21 may be used to predict, within 20% to 33%, the probable monthly mean values which may be observed in future years in Leicester, provided that the sources of pollution do not change appreciably. They may also be used, as in the next two paragraphs, as estimates of the daily mean pollution which would have been observed under average conditions of weather and emission.

4·212 *The seasons of the atmospheric pollution year* can be considered to be two in number, summer being the season when no artificial heating is required for human comfort, and winter being when artificial heating is a matter of course. There are also two intermediate seasons when heating is in partial use. Fig. 4·21 suggests that the months of April and October almost cover the intermediate seasons. In this report, therefore, May to September will be treated together as summer, and November to March as winter.

4·213 *The range of yearly variation of suspended impurity* may be estimated from the smooth curves of Fig. 4·21 as the ratio of the winter maximum to summer minimum.

TABLE 4·213 *Suspended Matter*

Ratio of winter maximum to summer minimum

	Central Stns. 1-4	Suburban Stns. 5-10	Country Stns. 11, 12
Smoke	4·1	3·8	2·6
SO_2 (volumetric)	3·4	2·3	1·9
SO_2 (lead peroxide method)	3·8	3·0	2·7

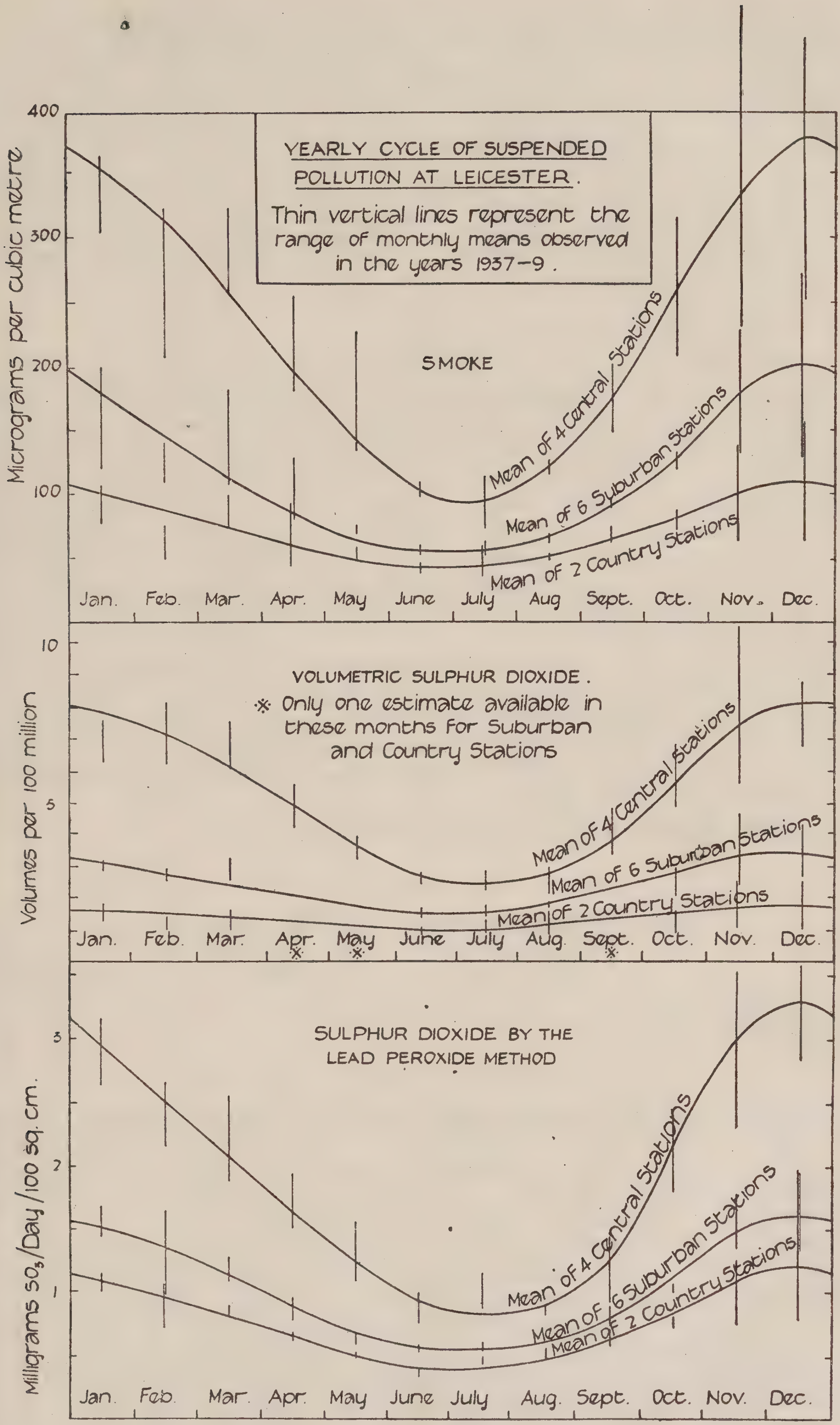

YEARLY CYCLE OF SUSPENDED POLLUTION AT LEICESTER.
Thin vertical lines represent the range of monthly means observed in the years 1937–9.
SMOKE
Micrograms per cubic metre
400
300
200
100
Mean of 4 Central Stations
Mean of 6 Suburban Stations
Mean of 2 Country Stations
Jan. Feb. Mar. Apr. May June July Aug Sept. Oct. Nov. Dec.
VOLUMETRIC SULPHUR DIOXIDE.
※ Only one estimate available in these months for Suburban and Country Stations
Volumes per 100 million
10
5
Mean of 4 Central Stations
Mean of 6 Suburban Stations
Mean of 2 Country Stations
Jan. Feb. Mar. Apr. May June July Aug. Sept. Oct. Nov. Dec.
SULPHUR DIOXIDE BY THE LEAD PEROXIDE METHOD
Milligrams SO3/Day/100 sq. cm.
3
2
1
Mean of 4 Central Stations
Mean of 6 Suburban Stations
Mean of 2 Country Stations
Jan. Feb. Mar. Apr. May June July Aug. Sept. Oct. Nov. Dec.

FIG. 4·21.

It is not surprising that the range in country and suburban air is less than in Central Leicester, where pollution from transport and distant towns must have the smallest relative effect. The range of variation of sulphur dioxide is less than that of smoke, as would be expected, because a bigger proportion of smoke is produced in domestic heating, which has a large seasonal variation. The difference between ranges for sulphur dioxide by the volumetric and lead peroxide method must be due principally to two differences between the methods: (a) the increased reactivity of lead peroxide when it is damp, coupled with the more prevalent dampness of winter (discussed in Section 2·613), and (b) the different effect of atmospheric ammonia on the two methods (discussed in Sections 2·513 and 2·614).

4·22 *Yearly Cycle of Deposited Matter.*

In Fig. 4·22 are plotted the monthly mean deposits of pollution at two stations in Leicester. Each plotted point is the mean of 5 or 6 deposits obtained during the given month in successive years. The variation from year to year was found to be even greater than with suspended pollution, and it was only after grouping 5 or 6 years' observations together that the yearly cycle was apparent. For this purpose it was necessary to make use of observations which had been made by the Leicester Public Health Department, and which had been published in the Annual Reports of the Investigation of Atmospheric Pollution.[1] The two new stations, numbers 3 and 7, at which deposit gauges were in operation during the Leicester Survey, provided insufficient results for inclusion in Fig. 4·22.

The smooth curves in Fig. 4·22 are estimates of the mean yearly cycle at stations 1a and 10, for the 6 years ended March, 1939. The three forms of deposited matter considered—namely, insoluble matter, dissolved matter, and sulphates—appear to follow very similar cycles, with the exception of insoluble matter at station 10, for which the monthly readings were too irregular for any periodic curve to be drawn.

4·221 *Range of yearly variation of deposited matter.*

TABLE 4·221 *Deposited matter*

Ratio of winter maximum to summer minimum

	Station 1a	Station 10
Total insoluble matter	1·6	1·0
Total dissolved matter	1·8	1·3
Sulphates	1·9	1·6

The yearly range of deposited matter is much less than of suspended matter given in Fig. 4·21. This is in agreement with the conclusion in Section 2·321, that, while smoke is mainly domestic in origin, deposited matter is mainly industrial. It was noted in Table 4·11 that the coal consumption for supplying industrial power would not be expected to have a yearly cycle.

In his "Statistical examination of data recorded by means of deposit gauges for the estimation of atmospheric pollution," B. H. Wilsdon[20] finds that gauges in London and Glasgow show a reversed annual variation of insoluble matter, with a maximum in summer. The Leicester gauges show no sign of this, although at Humberstone annual variation of insoluble matter is absent. It is conceivable that in London and Glasgow there is more industrial activity in summer than in winter. Wilsdon suggested[21] that there is a contribution from wind-blown dust. If this is correct, the different results of the Leicester gauges may be because they are not in parks like many of the London and Glasgow gauges. The gauge at Station 1a is on the Town Hall roof, 45 feet above street

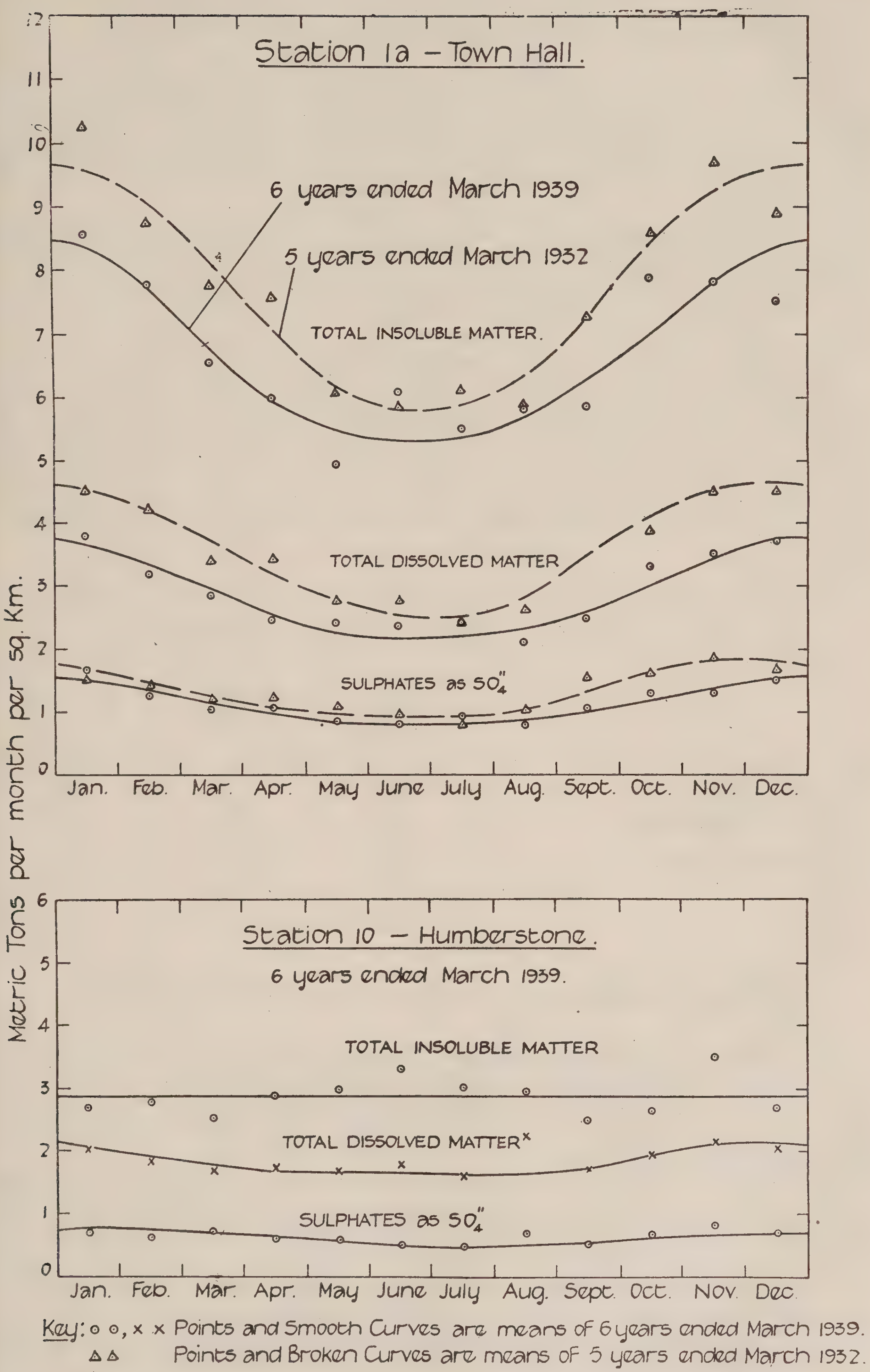


FIG. 4·22 YEARLY CYCLE OF DEPOSITED POLLUTION AT LEICESTER.

level, and might be expected to receive little dust blown from the street. Most of the roof is steeply sloping, so that little dust would collect on it. On the other hand there might be appreciable quantities of pollution from the Town Hall itself, where the flue outlet of the central heating boiler is 50 yards north of the gauge; there are also four chimneys serving open grates, each 25 feet from the gauge. This possibility is supported by the sharp differentiation, noticeable in Fig. 4·22, between the insoluble deposits during May to September and October to April. The central heating was only in operation during the latter months.

4·222 *Trend of deposited matter at the centre of Leicester.* For Station 1a, deposit gauge observations dating back to 1927 are available. The monthly means of the 5 years ended March, 1932, are plotted in Fig. 4·22, and it is evident at a glance that these means are in general higher than the smooth curves for the 6 years ended March, 1939. The figure only deals with three forms of deposited matter, however, and a statistical investigation has been made into the trend of all forms of deposited matter, of which Table 4·222 is the result. The 12 months of the year have been used to make 12 separate estimates of the ratio between the average rates of deposit during 1933-39 and 1927-32, but only the mean of the 12 estimates is recorded in Table 4·222. The difference of this mean ratio from 1·0 has been subjected to a standard test of significance, in accordance with Section 6·12. The results are recorded in the end column of Table 4·222.

TABLE 4·222 *Trend of deposited matter at the centre of Leicester.*

Ratio of deposit in 1933-39 *to deposit in* 1927-32.

	Ratio. $\frac{1933\text{-}39}{1927\text{-}32}$	Standard deviation of ratio	Comment
Total insoluble matter	*0·88	0·02	R
Tar (soluble in CS_2)	1·01	0·06	O
Other combustible matter	0·83	0·03	R
Ash	0·90	0·03	R
Total dissolved matter	*0·81	0·03	R
SO_4''	*0·86	0·03	R
Cl'	1·03	0·05	O
NH_4^+	1·51	0·11	I

* See also Fig. 4·22. I = Significant increase.
R = Significant reduction. O = No significant change.

With three exceptions, there appears to have been an all-round reduction of about 15% in deposited matter during the period considered. The reduction may have occurred because of improvements in industrial boiler technique, or in quality or amount of fuel used, or because of similar improvements at Leicester Town Hall.

One exception to this general trend is tar, which shows no significant change. For the purposes of deposit gauge analysis, all undissolved substances which are soluble in carbon bisulphide are classed as tar. It is possible that there was a small decrease of tar from combustion of coal during the period considered, but that this decrease was offset by an increase in the fumes from motor cars. The second exception is chloride-ion, which also shows no significant change. It has not been finally settled whether the small deposits of chloride-ion which occur in this country are partly due to the combustion of coal, or whether they are chiefly due to the evaporation of sea spray. The latter explanation seems to be supported by Table 4·222. On the other hand it is noted in Section 3·43 that more chloride-ion is deposited in Central Leicester than in the suburbs.

This is incompatible with a purely maritime origin. The third exception is ammonium-ion, which shows a significant increase.

4·23 *Monthly Mean Flux of Ultra-violet Daylight.*

Those who are interested in photography know how much the illumination of daylight varies with time of day, season of the year, and also with varying cloudiness. As a result of random variations of cloudiness, for example, more than three times as much daylight may be received on one day as on the next, and even by averaging observations for a month at a time the effect of variable cloudiness is not smoothed away. Smoke is not generally so effective as clouds, but it, too, brings about considerable reductions in daylight. These statements refer to visible daylight, but they are equally applicable to ultra-violet radia-

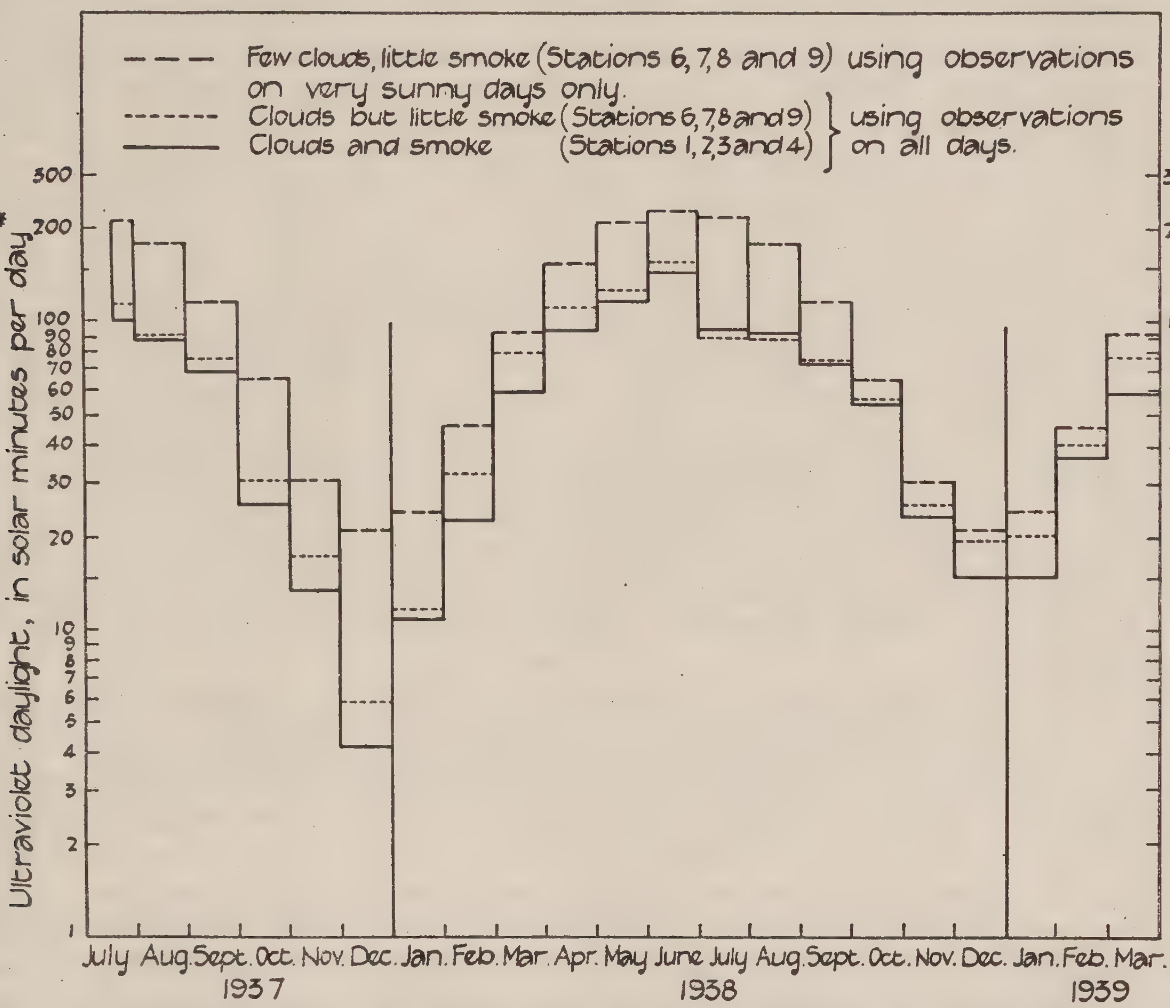


FIG. 4·23 THE MARCH OF ULTRA-VIOLET DAYLIGHT AT LEICESTER.

* The standard source is the sun at altitude 45° in a clear blue sky.

tion, which was measured in Leicester because of its therapeutic value. Daily observations of ultra-violet daylight were made in Leicester for $1\frac{3}{4}$ years, using integrators of the kind described in Section 2·7. The duration of these observations was not enough to permit accurate evaluation of the yearly cycle, although it is evident from Fig. 4·23, and from common experience, that a well-marked yearly cycle exists.

In Fig. 4·23 is plotted the monthly mean flux of ultra-violet daylight during the period of the observations. Stations 1, 2, 3, 4 are grouped together to represent Central Leicester, and Stations 6, 7, 8, 9 are grouped to represent the outer suburbs. At the outer stations, much less daylight is likely to be lost because of smoke than at the central stations. The scale of Fig. 4·23 is logarithmic, and the flux of ultra-violet radiation is expressed in standard natural minutes per day, where the standard source is the sun at an altitude of 45° in

a clear blue sky. The monthly mean flux ranges from 4 to about 150 standard natural minutes per day, and this would be difficult to show on a linear scale.

The light lost by the central stations during each month is represented by the rectangle between the continuous line and the dotted line, but the height of the rectangle represents the proportional loss, not the absolute loss. Thus the rectangles for December, 1937, and February, 1938, are equal, and they each represent a loss of 30%; the ratio of the central to suburban ultra-violet light is 4·2 : 6 for December, 1937, and 25 : 33 for February, 1938. The absolute amount of light lost in December was only 1·8 standard natural minutes per day, as against 9 in February. The percentage loss of light in Central Leicester is greatest in winter, as was pointed out in Section 3·42.

The difference between the summer and winter loss of light in Central Leicester (as compared with the outer stations) is partly due to the greater pollution in winter. It is also partly due to the greater obliquity of the sun's rays in winter, so that the same amount of pollution will reduce the light more in winter than in summer. It is not possible to calculate this effect accurately since it is complicated by light from the sky as well as from the sun. However, it is interesting to examine the difference between the summer and winter loss of ultra-violet daylight, due to smoke, at the central stations. The average loss in the summer months of May to September amounts to 5·8% and in the winter months of November to March to 23·1%. At first sight this would suggest that there was about 4 times as much smoke in the winter months as in the summer months, but in view of the greater obliquity of sunshine in the winter the number 4 is likely to be much too high. The observed ratio of winter to summer smoke concentration in Central Leicester for the same period was 2·4.

Expressing the winter loss in another way, and taking into consideration that Stations 6, 7, 8, 9 are not entirely smokeless, it can be deduced that at least 30% more ultra-violet daylight would have reached Central Leicester in winter if all the smoke were eliminated. On many individual days the losses were still higher, and occasionally more than half the possible ultra-violet daylight was obscured by smoke.

Although the observations are insufficient to permit accurate evaluation of the yearly cycle of monthly mean ultra-violet daylight, they will permit an approximate estimate of the yearly cycle of the ultra-violet daylight received on cloudless or nearly cloudless days. With the aid of meteorological observations made by the Leicester Health Department at the City General Hospital (Station 9), days were selected when more than two-thirds of the possible sunshine was recorded and when there was no evidence of cloud near midday. The contribution to the total flux of daylight when the sun is low had been shown to be so small that the loss of accuracy by including days which were cloudy near sunrise or sunset could not be large. In all, 64 days passed the test. The mean observed ultra-violet daylight on these days at Stations 6, 7, 8, 9 was plotted and a smooth curve of annual variation was drawn, which was found to be symmetrical about the summer and winter solstices. The standard deviation of points from the curve was 43%, and it follows that the curve was likely to be accurate to about 5%.

The monthly step-wise curve corresponding to the smooth curve for cloudless days is plotted as the upper broken curve in Fig. 4·23. The differences between it and the curve for all days at Stations 6, 7, 8, 9 must be due principally to clouds. A first inspection shows that the losses due to clouds are considerably greater than the losses due to smoke, which were discussed above. The average daylight losses due to clouds have little seasonal variation. The figure shows that the removal of all clouds would have increased the ultra-violet daylight by 60%. It will be recalled that removal of all smoke in winter would have increased the ultra-violet daylight by 30% in Central Leicester.

When daylight integrators are used for investigating the effects of atmospheric

pollution, it is evident that they should be used in pairs, one instrument being under the smoke and one out of it. For meteorological purposes, only one instrument is needed.

4·3 Weekly Cycle of Suspended Matter

Observations which are taken at intervals of a day or less may be examined to see whether they undergo a weekly cycle. Discussion of results is greatly simplified by the absence of a weekly weather cycle, but, as Table 4·11 suggests, the human causes of weekly cycles are complicated.

In Leicester, as in most English towns, there was a very great reduction in industrial activity on Saturday afternoons and Sundays, and also on Bank Holidays. It is to be expected, therefore, that the rate of deposition of solid matter would be much reduced at week-ends. It would have been of interest to investigate this at Leicester, but no instruments for recording daily deposits were available, and the time required to design and operate them was considered to be prohibitive.

In Section 2·321 it was shown that particulate pollution from industrial furnaces contains about 70% ash, and for many purposes it was convenient to ignore the industrial emission of combustible matter—i.e. smoke. But if industrial furnaces contribute only 20% of the total smoke on weekdays, there will be a 20% reduction at week-ends when the industrial fires are out or banked up, and this is comparable with the increase or decrease which might be expected in domestic smoke. The weekly cycle of industrial fuel consumption is so pronounced that it may considerably influence the weekly cycle of suspended smoke, particularly in the absence of a strong weekly cycle in domestic consumption of coal. Without careful measurements it is difficult to say whether more or less coal is used domestically at week-ends than during the week. It is probably safe to assert that less coal is burned on Sundays between 6 and 9 h., but later in the day more coal is burned, either for cooking the Sunday joint or to warm an extra room.

The weekly cycle of sulphur dioxide, on the other hand, would be expected to be controlled, in industrial districts, by the industrial consumption of coal, and to show a considerable reduction at week-ends. Thus the weekly cycle of sulphur dioxide in Leicester is easier to understand than the weekly cycle of smoke.

4·31 *Weekly Cycle of Daily Mean Readings.*

The apparatus for measuring daily mean concentrations of smoke and sulphur dioxide has the advantage that it eliminates the strong daily cycles which are discussed in Section 4·4. On the other hand, it tends to smooth out any short-lived variations such as the effect of Saturday afternoon. The practice at Leicester was to change all records at a time near to sunset, so that each daily mean concentration referred to daylight hours together with the previous night. For the present purposes, therefore, Sunday must be regarded as the daylight hours of Sunday, together with the night of Saturday to Sunday.

Table 4·31 presents the principal feature of the weekly cycle of smoke and sulphur dioxide, for each of 12 Leicester stations. The numbers tabulated are values of the ratio *mean concentration on Sundays and Bank Holidays* to *mean concentration on other days*. All observations in the period May, 1937, to March, 1939, have been included in the calculation, except those in the months of April and October. Stations 1, 2, 3, 4 are grouped together because by their nearness to industrial or commercial districts they might be expected to have a large weekly variation. Stations 6, 7, 8, 9 are grouped to represent suburbs. Stations 5 and 10 are in mixed districts and are best left ungrouped, together

TABLE 4·31 *Weekly cycle of smoke and sulphur dioxide concentration.* Ratio of mean concentration on Sundays and Bank Holidays to other days.

Station No.	Smoke		Sulphur Dioxide	
	Summer	Winter	Summer	Winter
1	0·65	0·68	0·65	0·64
2	0·66	0·79	0·61	0·63
3	0·63	0·83	0·66	0·67
4	0·66	0·77	0·45	0·60
Mean ..	0·65	0·77	0·59	0·64
6	0·89	0·85	0·61	0·70
7	0·81	0·69	0·66	0·77
8	0·78	0·80	0·86	0·69
9	0·78	0·85	0·67	0·85
Mean ..	0·82	0·80	0·70	0·75
5	0·69	0·89	0·75	0·75
10	0·75	0·92	0·59	0·77
11	0·93	0·87	0·66	0·93
12	0·83	0·80	0·70	0·76

with the country stations 11 and 12. High values of the ratio indicate a small weekly cycle and low values a large weekly cycle.

Because of the variations of weather, the individual fractions in Table 4·31 have large standard errors, but the differences between them are more accurate since weather generally affects all stations alike. The following conclusions are statistically significant:

(a) the weekly cycle for sulphur dioxide is larger than for smoke;
(b) the weekly cycle at Stations 1 to 4 is larger than at Stations 6 to 9;
(c) the mean ratio for each group of stations is significantly less than 1·0.

Conclusions (a) and (b) are consistent with the considerations of Section 4·31. Conclusion (c) is evidence that less smoke is found on Sundays than weekdays even in the residential districts of Leicester.

4·311 *Weekly cycle of emission.* Table 4·31 is not a good approximation to the weekly cycle of *emission* in the neighbourhood represented by the various stations, because much of the pollution at a given station must necessarily have been emitted elsewhere. If it were true that the other districts underwent a weekly cycle of the same proportional range, then this would not matter, and all districts would have similar weekly cycles. But this is not true in Table 4·31, for the more urban stations have the greater proportional range of weekly variation.

In Sections 3·51 and 3·52 an empirical way of correcting for pollution emitted elsewhere is described. When 0·9 times the lowest mean concentration of the 12 stations is subtracted from the remaining mean concentrations, the residues are approximately proportional to the emission at each station. Table 4·311 has been made by applying this correction to the data from which Table 4·31 was derived.

Stations 11 and 12 have been omitted from Table 4·311 because their observations were used in correcting for exotic pollution. The results are similar to Table 4·31, but they indicate that the weekly cycle of smoke emission in central districts is larger than the corresponding cycle of smoke concentration. They also indicate that the weekly cycle of emitted pollution is on the whole more pronounced in summer than in winter. These conclusions are to be expected if the weekly cycle is chiefly caused by the Sunday closing of shops and factories.

TABLE 4·311 *Weekly cycle of emission of smoke and sulphur dioxide*
Ratio of estimated emission on Sundays and Bank Holidays to other days.

Station No.	Smoke		Sulphur Dioxide	
	Summer	Winter	Summer	Winter
1	0·60	0·65	0·65	0·64
2	0·59	0·77	0·57	0·61
3	0·55	0·81	0·64	0·74
4	0·59	0·73	0·34	0·57
Mean ..	0·58	0·74	0·55	0·64
6	1·22	0·82	0·56	0·70
7	0·84	0·46	0·68	0·86
8	0·73	0·76	1·00	0·68
9	0·70	0·83	0·64	1·00
Mean ..	0·87	0·72	0·72	0·81
5	0·60	0·90	0·77	0·76
10	0·68	0·68	0·52	0·79

If, as is supposed in Section 3·6, the sulphur dioxide emitted is proportional to the coal burned, Table 4·311 can be particularly instructive. On this hypothesis, little more than half as much coal is burned on Sundays as on weekdays in Central Leicester, and about three-quarters as much in the suburbs. If it is now also assumed that the coal burned domestically has little or no weekly cycle, and that no coal is burned industrially on Sundays, it follows that more than half the total coal burned in central Leicester is for domestic purposes. On the same assumptions, three-quarters of the coal burned in the suburbs is for domestic purposes. It should be noted that the coal burned at the power station to generate electricity for domestic use has been included with coal burned domestically.

If domestic consumption of fuel could be made smokeless, considerably more than half the smoke of Leicester would disappear. It is of interest to compare similar estimates for other districts than Leicester. For London, by essentially the same method, Shaw and Owens concluded that the domestic fire is responsible for something over two-thirds of the total smoke.[27] In Great Britain as a whole it can be calculated from fuel statistics that about half the smoke is of domestic origin. For comparison with the weekly cycle of pollution, it would be of great interest to obtain figures of the domestic and industrial coal consumption in Leicester and other towns, but none are at present available.

4·32 *Weekly Cycle of Hourly Readings.*

Although the four automatic filters at Stations 1, 2, 3, 4 and the hourly sulphur dioxide apparatus at Station 1(b) were designed chiefly to measure the daily cycle of suspended pollution, their results can theoretically be applied to estimate the weekly cycle, hour by hour. The strong daily cycle can be eliminated by expressing each hourly reading as a ratio to the average value for that time of day. The usefulness of this kind of test is much reduced, however, by the great variability from day to day of suspended pollution at any given hour of day. Thus, the standard error of the mean of 40 readings of smoke at 8 h. on winter Sundays was about 15%, and even greater errors are to be expected earlier in the morning. Hence to be reasonably sure that a variation of, say, 10% is not a random error, the standard error of the mean may not exceed 5%, so that the mean of at least 360 readings is required. But as there were only 156 week-ends in the whole Leicester Survey, this degree of accuracy was quite unattainable.

Standard errors cannot be much reduced by grouping three or four consecutive hours together, for the means at successive hours are interconnected. The chief cause of variability is atmospheric turbulence, which may change very much from day to day, but only slowly from hour to hour. For example, a chance tendency for Sundays to be less turbulent at 8 h. than other days of the week would almost certainly be accompanied by a similar tendency at all times between 6 and 10 h. There is little to be gained, for the same reason, by grouping several stations together.

An examination of the automatic filter records for the four stations of central Leicester revealed that the only significant reductions of smoke at week-ends occurred between 5 and 20 h. on summer Sundays and from 4 h. on winter Sundays to 6 h. on the next day. During most of the time these reductions were fairly steady, but between 6 and 8 h. in both summer and winter the reduction was particularly great. The average concentration of smoke during daytime on summer Sundays was about 50% of the normal weekday concentration, and on winter Sundays about 70%. Between 6 and 8 h. on summer Sundays the average concentration fell below 30% of the normal, and on winter Sundays below 40%. Evidently the closing of factories and business premises on Sundays was responsible for the general reduction, and the deep minimum between 6 and 8 h. was an additional effect due to the need for the population to be up betimes on weekdays.

Sulphur dioxide at Station 1(b) was reduced slightly more than smoke at week-ends, and the reduction started earlier. In both summer and winter, significantly less than the normal concentration of sulphur dioxide was found between 5 h. on Saturday and 5 h. on Monday. A deep minimum, similar to that of smoke, occurred between 7 and 9 h. on Sundays. The subnormal concentrations of sulphur dioxide on Saturday mornings may be due to a tendency for factories to consume less power on Saturdays, but such an unusual experimental result requires confirmation. As a check on the method of determining the weekly cycle from hourly readings, estimates similar to those of Table 4·31 were calculated from hourly observations. It was found that agreement was within 4%, with one exception which appeared to be due to the faulty operation of an automatic filter. The estimates from hourly observations of sulphur dioxide at Station 1(b) agreed within 4% with the means of corresponding estimates in Table 4·31 for Stations 1 and 2.

4·4 Daily Cycle of Suspended Matter

Observations with automatic filters have been made regularly since 1920 at different points in Great Britain, and the daily cycle of smoke concentration has been discussed in the annual reports of the Investigation of Atmospheric Pollution.[8] It is marked by a maximum at about 9 h. and another in the afternoon. Usually the morning maximum is the higher of the two, and in some places in winter the smoke concentrations in the middle part of the day are high enough to cause the evening maximum to disappear. On individual days there may be departures from the normal daily cycle, but these can usually be attributed to abnormal changes in weather.

The principal causes of the daily cycle are all connected either with human habits or weather, if solar heating is included as a form of weather. It is a general fact that coal fires of all kinds give most smoke shortly after they have been lit, and that those with hand stoking produce additional smoke when being refuelled. It is natural, therefore, that there should be a maximum smoke concentration in the morning, shortly after domestic and industrial fires have been lit. But the evening maximum cannot be so simply explained. It has been attributed to refuelling and lighting additional domestic fires, and to the banking up of some industrial fires for the night, but this explanation is inadequate

because it fails to account for the similar evening maximum in the cycle of sulphur dioxide. However, a satisfactory qualitative explanation is possible when meteorological factors are considered. It is given in a paper by F. J. W. Whipple,[22] and similar conclusions are reached from the Leicester results in Section 4·42.

The meteorological causes of the daily cycle are the same as those which produce fogs. When ordinary inland fogs form, the main cause is a cooling of the surface layers of air in contact with the ground. Unless a considerable breeze is blowing, the cooling slowly spreads to a thicker and thicker layer of air, which cannot mix with the air above it. Any smoke within this layer can escape from it only by deposition. The worst smoke concentrations will tend to occur when the cool layer extends above the chimney tops, and the lowest concentrations will tend to occur when no cool surface layer exists, so that smoke may mix to great heights. The cool layer forms most frequently at about sunset, and often persists until several hours after sunrise. Thus there is a meteorological reason for high concentrations of smoke both in the evening and early morning.

It is theoretically possible for the cool layer to be responsible for local low concentrations of pollution near the ground. An anomalous low concentration might be observed when the cool layer includes the measuring instruments but does not include the chimney tops. A still more probable cause of occasional low records of pollution in fogs is the fact that, within the cool layer, mixing is often strongly inhibited, so that pollution might take a long time to diffuse from the chimney tops down to the level of the instruments. There is evidence that this phenomenon is quite common in the case of sulphur dioxide and smoke emitted from high chimneys. Indeed, the smoke trails from isolated industrial chimneys can frequently be seen extending for several miles without apparently making contact with the ground.

While the daily cycle of smoke has been for some time attributed to a diarchy of solar phenomena and human habits, the problem of distinguishing their respective spheres of influence has proved difficult. The Leicester Survey provides two new approaches to this problem; one which uses the fact that sulphur dioxide is not emitted excessively when fires are lighted or stoked, and one which uses observations of the daily cycle of atmospheric turbulence.

4·41 *Daily Cycle of Smoke and Sulphur Dioxide.*

In Fig. 4·41 the daily cycles of smoke and sulphur dioxide are compared in summer and winter so far as observations permit. The only hourly observations of sulphur dioxide were at Station 1(b), but there were no smoke observations at this station. However, the daily mean concentration of sulphur dioxide at Station 1b was found to agree closely with the mean of volumetric observations at stations 1 and 2. The best smoke estimates which are available for comparison with hourly sulphur dioxide at Station 1b are therefore the means of the hourly automatic filter readings at Stations 1 and 2. To make the comparison of smoke and sulphur dioxide more striking in Fig. 4·41, sulphur dioxide is expressed as volumes per 238 million. The mean concentration during winter nights between 18 and 5 h. is then numerically the same as the mean smoke concentration.

In winter, smoke follows the sulphur dioxide cycle closely during the hours of darkness. During daylight excessive smoke is produced between 7 and 9 h. on weekdays and 8 and 10 h. on Sundays. On summer weekdays the smoke is in excess during the night as well as the early morning, but the greatest excess again occurs in the early morning. There is evidence that the observations on summer Sundays are either not sufficiently accurate or are disturbed by other impurities such as ammonia. Fig. 4·41 confirms that the extra height of the morning maximum of smoke concentration is because coal is burned particu-

larly inefficiently at these hours of the day. On the other hand, it provides no evidence of unduly inefficient combustion during the evening. A special investigation was made of the records for April and October, to see whether there was a tendency to burn extra coal in the evening, or to burn it inefficiently.

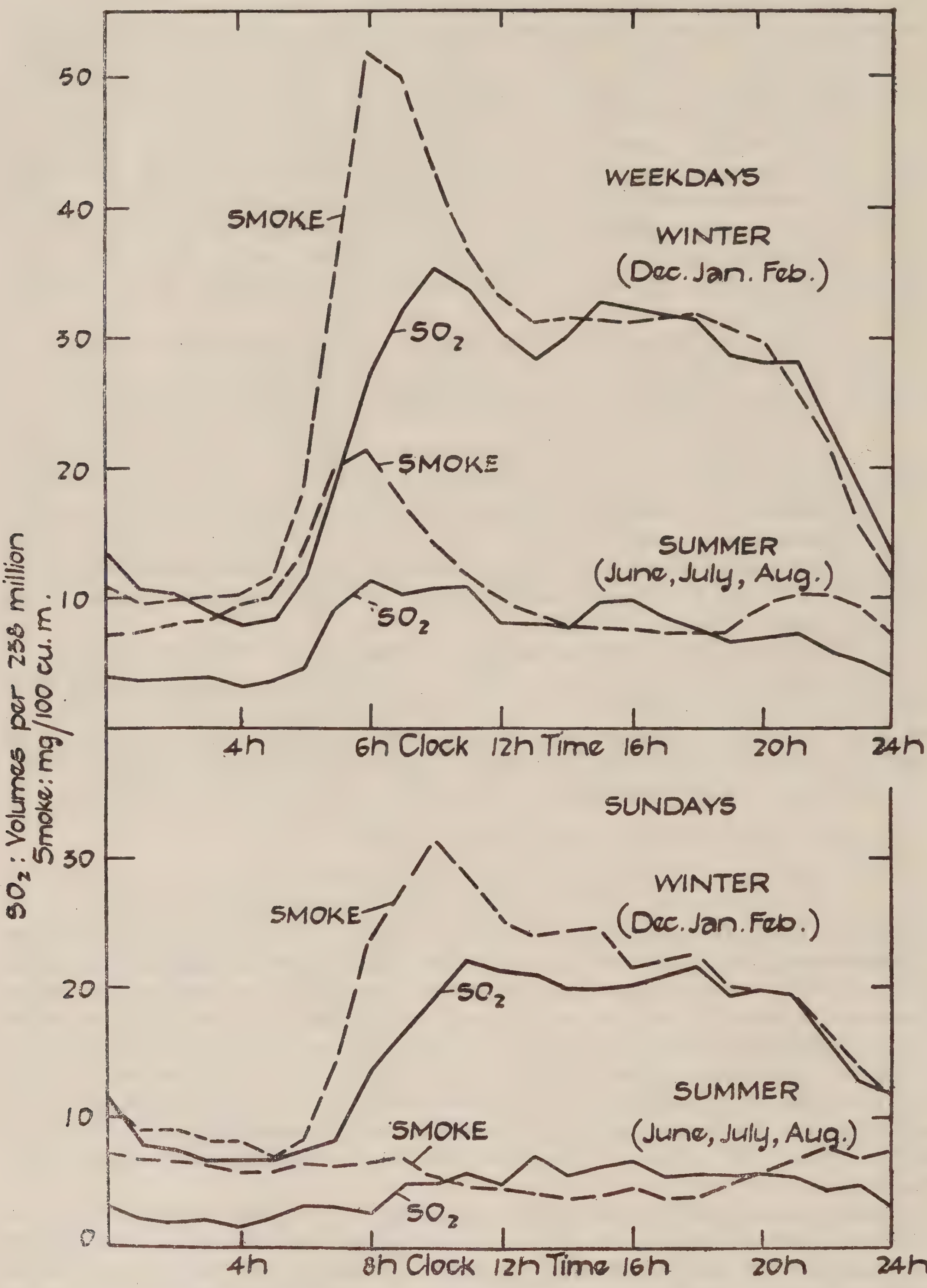


Fig. 4·41 Daily Cycle of Smoke and Sulphur Dioxide.

Sulphur dioxide concentrations were measured at Station 1b. Smoke concentrations were measured at Stations 1 and 2, and the mean taken. Sulphur dioxide was expressed in special units in order to have the same numerical mean as smoke during winter nights between 18 h. and 5 h.

No such tendency could be detected. April and October were chosen because in these months the days are often warm while the evenings are cold enough for a fire. It seems that the evening maximum is attributable chiefly to effects of the daily cycle of turbulence.

4·42 *Daily Cycle of Atmospheric Turbulence.*

Many phenomena of weather depend on the rate at which air mixes with itself. If a small volume of a foreign gas is set free into the air, it will of course travel with the wind, but it will also diffuse and become mixed with larger and larger masses of air, so that its maximum concentration, wherever this may be, is always decreasing. The rate of this decrease evidently depends on the rate at which air mixes, but the process is not yet fully understood, and there is no simple way of assigning a numerical value to it. It is known, however, that ordinary molecular diffusion plays a negligible part in the process of mixing, unless the air is completely still, and therefore a suspensoid such as smoke will become diluted at very nearly the same rate as a gas. The fact that atmospheric pollution is emitted not at a single point but at a large number of points is an added complication, for lateral diffusion cannot greatly alter smoke concentrations in urban areas, while the rate of vertical diffusion is of paramount importance.

Although no simple measure of turbulence is known at present, there are two measurable atmospheric conditions which are closely related to turbulence. The first is vertical temperature gradient—the rate of change of air temperature with height. In the air as a whole, temperature decreases with height and the gradient is negative; but in special conditions, when there is a cool layer near the ground, the gradient may be positive and air temperature may increase from the ground up to heights varying between a few inches and thousands of feet. Just as water cannot circulate when it is heated from above or cooled from below, it is found that air in a positive temperature gradient does not readily mix vertically, and its turbulence is small. Meteorologists are familiar with atmospheric temperature gradient, although it is not one of the routine observations at climatological stations. The usual meteorological expression, "lapse rate," is the temperature gradient with its sign changed, i.e. the rate of *diminution* of temperature with height. Hence lapse rate is positive in the air as a whole, and a negative lapse rate is a sign of stability and poor mixing.

The second condition is change of wind velocity with height (wind velocity gradient). As a rule, low wind velocity gradient corresponds to strong turbulence. The difference between the wind velocity at a point near the ground and at a higher point is thus a measure of turbulence, though like lapse rate or temperature gradient it is not a perfect measure.

Temperature gradient and velocity gradient occur together in a formula,[23]

$$R_i = \frac{g}{T}\left(\frac{\delta T}{\delta z} + \Gamma\right) \Big/ \left(\frac{\delta u}{\delta z}\right)^2 \quad \text{(1)}$$

where R_i is called Richardson's number, g is the acceleration of gravity, T the absolute temperature of the air, Γ the adiabatic lapse rate, $\delta T/\delta z$ the observed temperature gradient, and $\delta u/\delta z$ the wind velocity gradient. When R_i exceeds a certain value variously estimated between $+0{\cdot}25$ and $+1{\cdot}0$, theoretical considerations show that turbulence should die out, and when R_i is less than the critical value turbulence should develop. Considerable research has been done on the stability of the surface layers of air over grassland and over the sea, but little is known about the air over a very irregular surface such as is presented by the buildings in a town. As soon as the work had shown the importance of turbulence, it was realized that measurements at Leicester of meteorological phenomena relating to stability should be started during the survey, although little time or equipment was available. Lapse rate and wind

gradient were therefore observed over grassland at Station 9; their daily cycles are plotted in Fig. 4·42, in terms of differences of readings at 9·8 and 5·2 metres respectively.

Lapse rate was observed hourly for 13 months, from December, 1938, to December, 1939, inclusive. Two thermocouples in series were used as thermometers. They were mounted in louvred housings attached to a mast at 5·2 metres and 9·8 metres above the ground, and the current was recorded photographically. On comparing with the results at Leafield (Oxon) of Johnson and Heywood,[31] who used aspirated platinum resistance thermometers, the average lapse rates during the daytime were found to be too small. This appeared to be the influence of direct solar radiation on the thermocouples, and it was necessary to reject all measurements made when the sun was shining. In Fig. 4·42(a), the hourly mean lapse rate is plotted for each season of three months, December, January, February being termed "winter," and so on. The dotted portions of the curves were estimated from Johnson and Heywood's results.

Wind gradient was observed for seven months, from June to December 1939, with two Robinson cup anemometers at the same two heights, whose counters were photographed hourly. Wind velocity does not increase uniformly with height, but increases most rapidly near the ground. Wind gradient therefore decreases with height, and can only be strictly determined from tangents to a curve representing the variation of wind velocity with height. What was determined at Leicester was the difference between the wind velocities at 9·8 and 5·2 metres, divided by the difference in height (4·6 metres). This would be equal to the wind gradient at some intermediate height, probably about 7 metres. The daily cycle of these determinations is plotted in Fig. 4·42(b).

Hourly values of Richardson's number were calculated by formula (1) from the above observations of lapse rate and wind gradient. The median daily cycle of these values was in agreement with the daily cycle derived by applying formula (1) directly to the curves of Figs. 4·42 (a) and (b). The latter is plotted for summer and autumn in Fig. 4·42(c), which gives the daily cycle of Richardson's number at a height of about 7 metres. The dotted portions of the curves are based on Johnson and Heywood's measurements of lapse rate.[31]

The importance of Fig. 4·42 from the point of view of atmospheric pollution is that it shows how the daily cycle of turbulence may distort the daily cycle of smoke and sulphur concentrations. It shows that, if the emission of pollution is constant, there should be a minimum concentration near noon and a maximum at night. It shows, further, that these effects should be much larger in summer than winter. In practice, the night maximum is completely masked by the reduction of emission at night, but it happens that the emission of pollution near noon is sufficiently uniform to show the noon minimum. In Fig. 4·41 for weekdays, there is a secondary minimum of sulphur dioxide near noon, which is equivalent to a reduction of about 10% in winter and 20% to 30% in summer. The noon minimum of smoke in winter is only about 2% less than the evening maximum, but is about 30% less in summer.

Figs. 4·41 and 4·42 do not give a satisfactory determination of the quantitative dependence of pollution on lapse rate, because other variables are not sufficiently constant through the day. Probably a decrease in lapse rate of 0·01° C. per metre—i.e. 0·0055° F. per ft.—would decrease pollution concentrations by 20% to 30%. This agrees well with the regressions of daily mean pollution on daily mean temperature gradient during October-December 1939, which are for sulphur dioxide 22% and for smoke 37% per 0·01° C. per metre.

On a basis of 25% per 0·01° C. per metre, it can be estimated that pollution emitted at night must cause an average of 4 times as great a concentration as the same amount of pollution emitted at midday in spring or summer. This would partly explain the high concentrations on summer nights in Fig. 4·41.

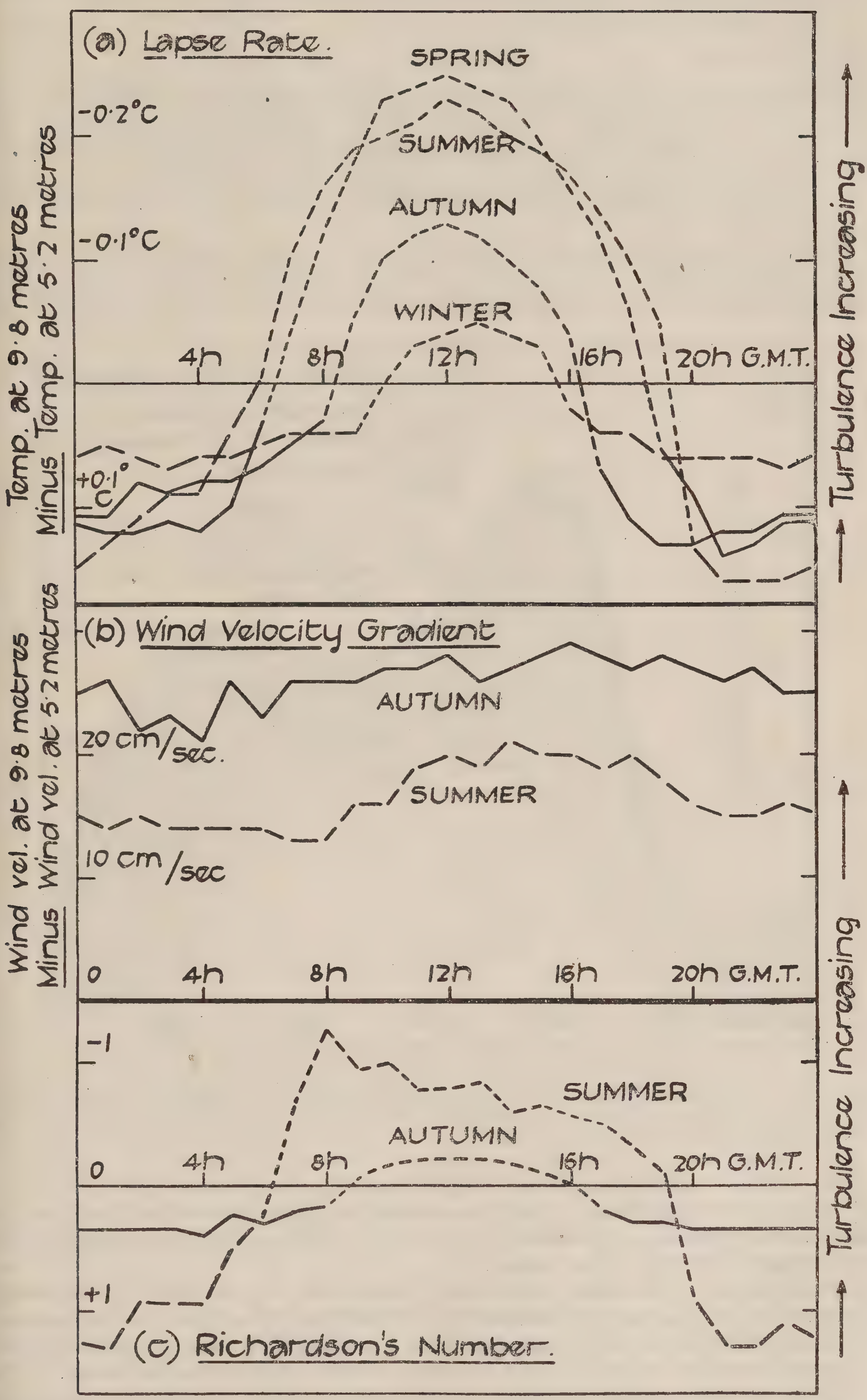


FIG. 4·42 DAILY CYCLE OF ATMOSPHERIC TURBULENCE.

an additional cause is the pollution produced during the previous day in neighbouring industrial districts.

4·43 *Conclusion*

To sum up, the daily cycle of pollution is produced by a combination of at least four factors: (a) coal consumption, (b) combustion efficiency (in the case of smoke), (c) turbulence, and (d) pollution from neighbouring districts. Fig. 4·43 shows how the four factors combine to give the daily cycle of smoke concentration. It represents mean conditions in March, and is approximately to scale.

The broken curve represents the daily cycle of coal consumption; or rather, of the smoke which would be produced if the coal were burned with average efficiency and the lapse rate were at its midday value throughout the 24 hours.

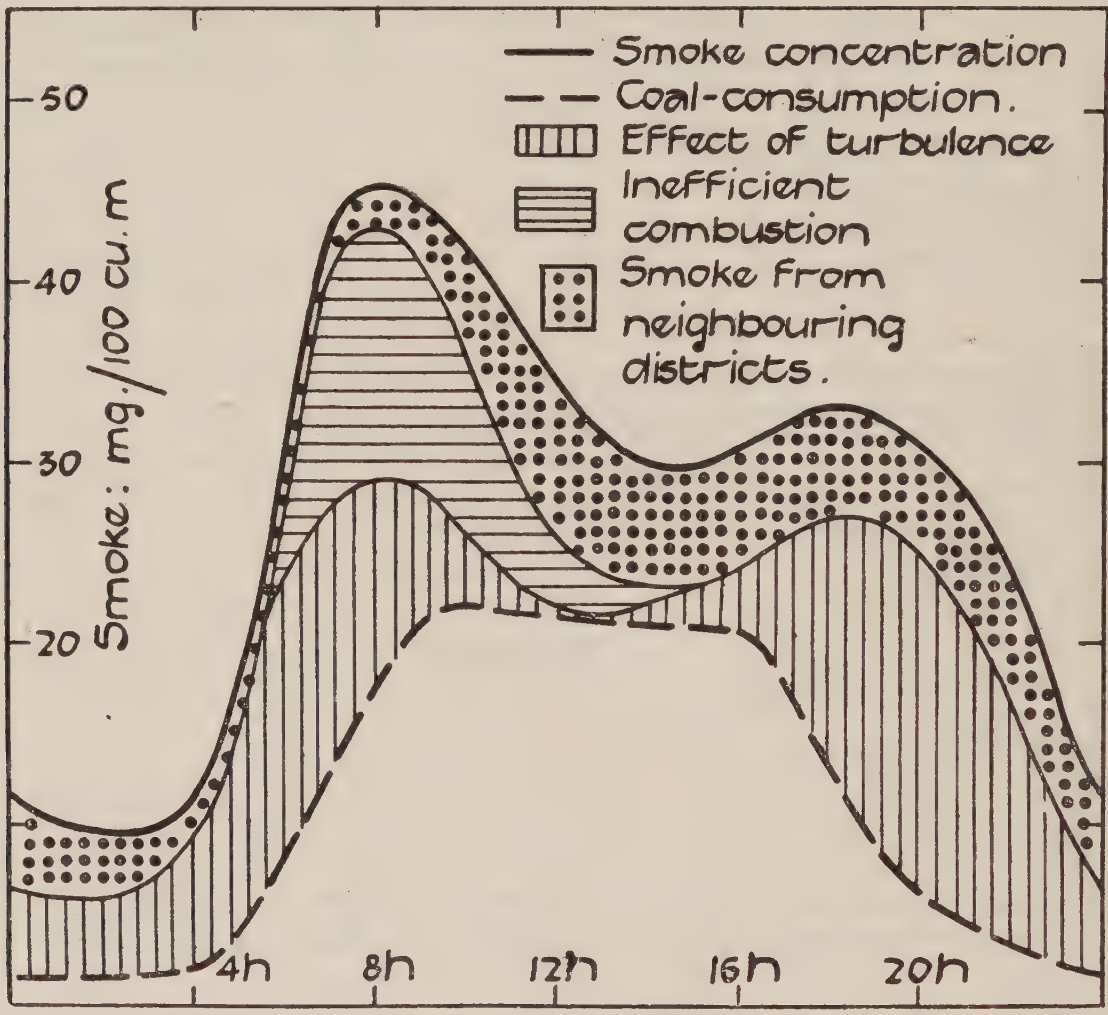


FIG. 4·43 CAUSES OF THE DAILY CYCLE OF SMOKE.

Note: The effect of turbulence is to reduce smoke concentration during the middle of the day. Turbulence is often low during the night, and the concentration of smoke is increased in consequence.

The vertical hatching represents approximately the effect of the daily cycle of turbulence during March: the effect would be greater in summer and less in winter. The greatest proportional increase of smoke is at night, but the greatest net increase is shortly after sunset.

The horizontal hatching represents the result of particularly inefficient combustion of coal during kindling and refuelling. The effect is greatest at 8 to 9 h., when about 50% extra smoke is produced. Finally the stippled area represents smoke brought by the wind from neighbouring districts. It is assumed that this smoke has taken four hours to come, and that it therefore undergoes a daily cycle which is four hours later than the daily cycle of Leicester smoke.

The smooth curve represents the actual cycle of smoke concentration brought about by this combination of causes. It is comparable with Fig. 4·41; the broken curve of Fig. 4·43, representing the daily cycle of coal combustion, was derived from it by reversing the order of the above discussion.

The smooth curve of Fig. 4·43 is typical of Leicester in March. Other towns will have different cycles of smoke, according to the ratio of domestic to industrial consumption of coal, and the distance away of their nearest neighbours. Thus the figure should only be regarded as a general guide to the way in which the complex and interesting daily cycle of smoke comes about.

A diagram similar to Fig. 4·43 would represent the daily cycle of sulphur dioxide, except that there would be no horizontally hatched area because inefficient combustion does not increase the amount of sulphur dioxide.

4·44 *Summer Time*

Twice a year in Great Britain the daily cycle of human activity shifts one hour in relation to the sun and the daily weather cycle—namely, when Summer Time begins and ends. It has often been suggested that these events may be used to separate the influence of the two cycles of atmospheric pollution.

In Fig. 4·43 the effect of a change of clock time is to displace the vertically hatched area (effect of turbulence) relatively to clock time, while the other features remain fixed. The morning maximum will move only slightly, as it is little affected by turbulence. The midday minimum will be displaced, however, and the evening maximum will probably be displaced by rather less than an hour. If Section 4·43 is a fair representation of the facts, then the midday minimum should be an hour later in British Summer Time than Greenwich Mean Time. The same argument is true for the daily cycle of sulphur dioxide, which has a more definite midday minimum than smoke.

There were four occasions when clocks were adjusted during hourly observations of sulphur dioxide, and the observations on the 10 weekdays before and after the change of time have been examined, so that there were four groups of 10 days in G.M.T. and four groups of 10 days in B.S.T. In G.M.T., to the nearest tenth of an hour, the midday minima of each group were at 13.5 h., 13 h., 12.5 h., and 13.1 h., the average being 13.0 h. In B.S.T. the times were 12.8 h., 14.8 h., 13.7 h., and 13.8 h., the average being 13.8 h. Hence on an average, the midday minimum was about $\frac{3}{4}$ hour later in British Summer Time than Greenwich Mean Time. A statistical test was made on this result, however, and it was found to have an accident-probability of 0·14. Hence, although the result is encouraging, it is not conclusive.

When a similar test was made on results with the four automatic filters, the daytime minima of groups of 10 days' data were found to be ill-defined. The time of minimum was uncertain over a range sometimes of 3 or 4 hours, and tended to be later in the day than the minimum of sulphur concentration. It seemed probable that the morning maximum, ascribed to inefficient combustion of coal in newly lit fires, was overlapping the period of maximum turbulence. The test was therefore unsatisfactory, because it was not possible to estimate the times of the daytime minima with sufficient accuracy. Using 22 groups of 10 days' observations, it was found that the mean shift of the morning maximum in changing from G.M.T. to B.S.T. was $\frac{1}{4}$ hour, the maximum being later in B.S.T. The standard error of the mean was estimated to be 7 minutes, and the mean must therefore be deemed significantly different from zero, since its accident-probability is only 0·03. That the morning maximum is a few minutes later in British Summer Time might be attributed to the daily cycle of turbulence, but an equally probable explanation is connected with human habits. There will be a tendency for the population to start its domestic activity rather later in the dark mornings at the beginning of summer time, in spite of having to begin work at the same hour of the clock. The automatic

filter at Station 1, in the commercial part of Leicester, does not show any shift of morning maximum, and therefore tends to support this explanation.

The effect of good mixing near noon is revealed when the smoke concentration at the daytime minimum is compared with the morning maximum. In Greenwich Mean Time, the morning smoke maximum is expected to be an hour closer to the period of maximum turbulence than in British Summer Time. Therefore if there is an overlap, the concentration of smoke at the minimum should be higher in Greenwich Mean Time than British Summer Time. The concentrations of smoke at the minimum in each 10-day group were expressed as fractions of the concentrations at the morning maximum, and the results were collected in pairs of which one member represented the 10 weekdays before each change of time and the other member the 10 weekdays after. In 19 out of 22 pairs of ratios available, the ratio was greater in Greenwich Mean Time than in British Summer Time. The probability that such a result should occur accidentally is about 0·0008; hence it may safely be concluded that the ratio minimum to maximum is higher in Greenwich Mean Time than in British Summer Time, when other circumstances such as temperature and length of day are as nearly equal as possible.

The effect of Summer Time is therefore as would be expected from Fig. 4·43, if proper allowance is made for casual errors. To put it briefly, part of the daily cycle follows the clock and part follows the sun. In consequence, care is needed in working up automatic filter results from all stations in Great Britain: *when calculating the seasonal average of the daily cycle of smoke it is usually better to consider a period which does not include a change of clock-time.* The seasonal averages appearing in the Annual Reports of the Investigation of Atmospheric Pollution have been calculated in this way.

4·5 Irregular Variation of Atmospheric Pollution

When people say "It's a dirty day," they are usually referring to the weather, although the expression might be used literally on many occasions, and the idiomatic usage is in a way regrettable. No instruments more reliable than the eyes, nose and skin are necessary for a townsman to distinguish whether one day is cleaner or dirtier than its predecessor!

Fig. 4·5 shows how very much the suspended pollution varied from day to day in the winter months of 1937-9. The smoke in central Leicester varied from less than $\frac{1}{4}$ of the mean to more than 4 times the mean; the sulphur dioxide varied over a similar range except that there were no observations higher than about 3 times the mean. It is quite evident that the distributions of smoke and volumetric sulphur dioxide are not normal in the statistical sense (see Section 6·12). The skewness is partly because the variance of pollution is so great and partly because negative concentrations are impossible. Though less pronounced, the same difficulty occurs in the frequency distribution of deposited matter for all months of the year. The frequency distribution of results for all months by the lead peroxide method shows two distinct maxima caused by seasonal variation.

It is fairly common knowledge that in brilliant weather, with bright cumulus clouds in a blue sky, the concentration of smoke is unusually low; and that pollution is high on days typified by stratus clouds or fog. In wet weather we cannot usually observe the smokiness directly, because rain interferes with all three sensory methods of observation, but it might be expected that rain would decrease the concentration of suspended pollution and increase the rate of deposition of pollution. In cold weather we have bigger fires and make more pollution, and in windy weather our own smoke is quickly removed, but only to be replaced by someone else's! Thus atmospheric pollution is connected in diverse ways with many aspects of weather.

If it were possible, the easiest way for a scientist to examine these connections would be to release a known amount of pollution in controlled weather conditions and make the requisite measurements, and then to vary one only of the conditions and repeat the measurements. After a thorough investigation of one particular weather condition, work would be started on the next, and ultimately a clear picture would be formed of the whole mechanism. This technique is used for many different researches, from the design of ships' hulls to the diet of white rats, but it cannot be applied to problems connected with weather. The only course open is to observe the weather as it changes, and the atmospheric pollution at the same time, and collect a large number of simultaneous sets of observations. When the number of sets appears to be sufficient,

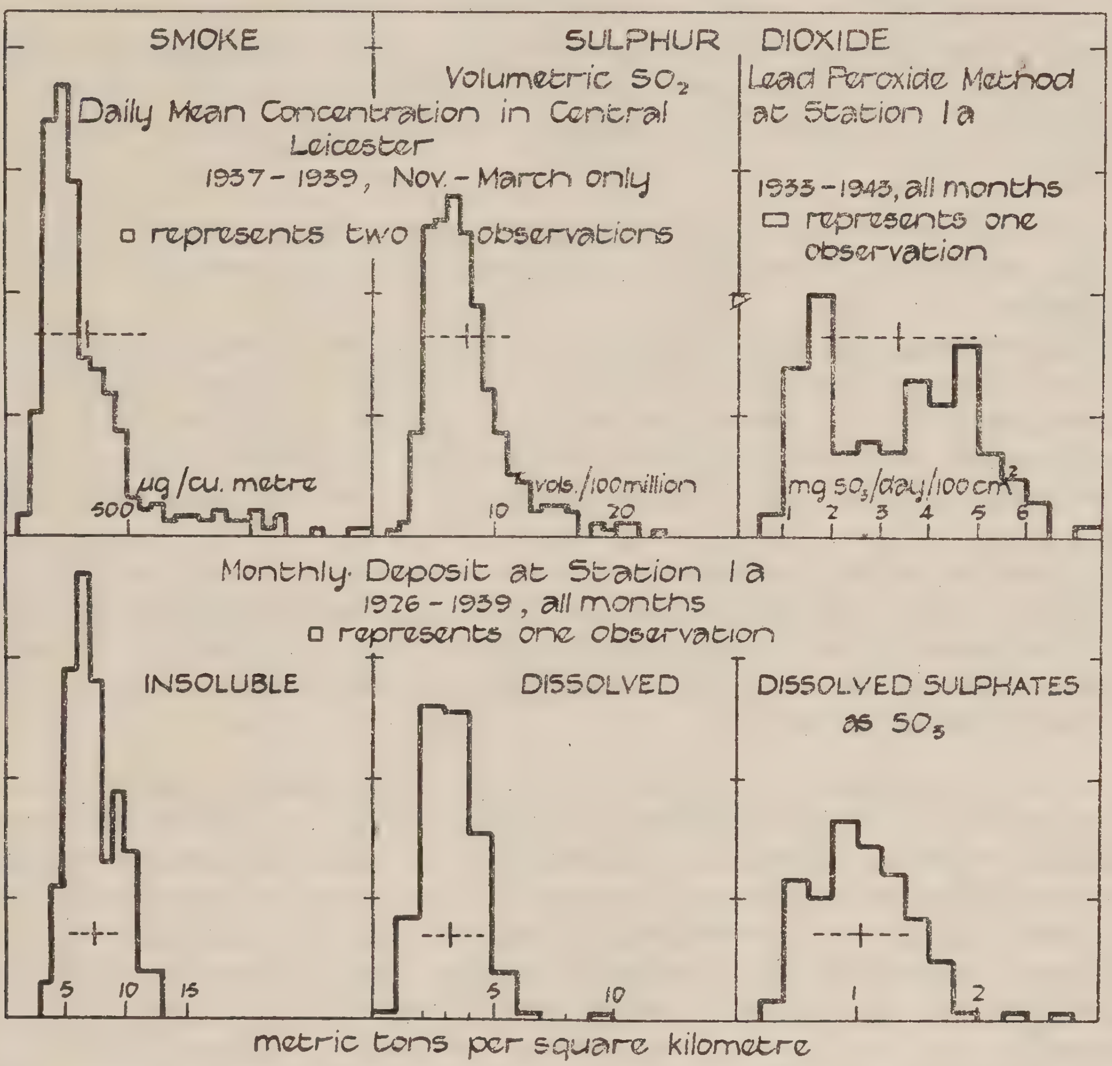


FIG. 4·5 FREQUENCY DISTRIBUTION OF POLLUTION.

The short vertical line on each diagram marks the mean. The broken line across it measures the square root of the variance (*i.e.* the standard deviation if the distribution is normal).

it is possible to begin disentangling the correlations between the variables of weather and of pollution. Two examples of how this work may be done are given in Appendix 6·1, but the best way for the newcomer to understand statistical technique is undoubtedly to practise for himself, reading at the same time one of the modern books on the subject.

It is not sufficient, however, merely to know to what extent variations of different kinds of pollution are correlated with different aspects of weather. It is necessary to know how the correlations are brought about. When there is an increase in turbulence, for instance, the smoke concentration will decrease because extra air is being mixed with the smoke. On the other hand, when the weather turns warmer the smoke concentration will again decrease, this time

because less smoke is being produced. These are straightforward examples, bu sometimes a correlation occurs because of the effect of weather on the measurin apparatus; for example, a surface of lead peroxide is more reactive when wet and then estimates of sulphur dioxide are artificially high.

A very common cause of correlation is the occurrence of regular periodi cycles both in weather and pollution. At nighttime, for instance, less pollutio is made because people are in bed; also the temperature is lower than durin the day. Hence if we measured smoke and temperature at various times o day and night, without considering these daily cycles, we should find the pair of observations were correlated, there being a marked decrease in smoke whe there was a decrease in temperature. We should get the result that the colde the weather the less the smoke. This is quite absurd, when taken from it context, because the correlation is indirect. The direct connections are betwee the sun and temperature, and between the sun, coal consumption, and pollution It is possible to obtain correct correlation coefficients, however, in spite of th presence of periodic cycles. The methods of eliminating periodic cycles are fou in number.

(1) By taking the mean observation over one or more complete cycles—e.g daily mean smoke, sulphur dioxide, wind velocity, monthly mean rate o deposit.
(2) By expressing an observation as the ratio to the corresponding magnitud expected from the smooth curve of periodic variation—e.g. the smok concentration in Central Leicester on the 20th October, 1938, was 42 micrograms per cubic metre, whereas from the yearly cycle of Fig. 4·2 the expected value was 278 micrograms per cubic metre; so that the rati is 1·52.
(3) By using a single observation at a given moment or stage of each cycle— e.g. daily lapse rate observations at 7 a.m., or daily minimum temperature
(4) By excluding from consideration observations occurring at an irregula part of the cycle—e.g. excluding Sunday observations of such pollutio as has a weekly cycle.

The careful elimination of periodic cycles is a safeguard against misleadin conclusions about the correlation of variables which vary erratically as well a periodically. On the other hand, if variable x affects variable y, the periodi cycles of x will occur in the variations of y. For example, daytime turbulenc has a yearly cycle, with a minimum in winter. This affects the yearly cycle o smoke and sulphur dioxide, intensifying their winter maxima. Thus, in thi case, eliminating yearly cycles increases the risk that a correlation may pas unnoticed.

Certain of the correlations to be considered are between different kinds o pollution at the same place, or one kind of pollution at different places. I others, different kinds of pollution at different places are correlated with weather observations. Pollution varies very much from district to district, but in the present context weather may be regarded as uniform over the whole area of the Leicester Survey, and this is a useful simplification.

Perhaps it is well to end this introduction on a note of pessimism, or at any rate scepticism. The statistical method will give valuable indications about why atmospheric pollution varies, and how it may therefore be dealt with, and there is at present no better method available. But the number of pitfall increases rapidly with the number of variables, and there are many variable concerned with the time variations of atmospheric pollution. The conclusion to be found in the remainder of this chapter may therefore be modified considerably when more elaborate investigations can be made, but it is hoped that they will prove to be useful meanwhile, besides providing a basis for further researches.

4·51 *Degree of Irregular Variation*

The degree of irregular variation is best measured by variance, which is described in Section 6·12. The square roots of the variances are indicated in Fig. 4·5 for six forms of pollution. The variance of a group of measurements is the average of the squares of the individual differences from the mean, except that the average is found by dividing by one less than the total number of measurements; this allows for the mean to be calculated from the same group of observations. The variance of a group is independent of the size of the group, and, apart from its own irregular variations, is the same for any group drawn at random from a given "population." Thus if the given population is the monthly rainfall in a certain deposit gauge, the variance would be the same whether it was calculated from 600 (50 years') observations, from 50 single observations picked at random from this population, or, with reservations, from 36 observations occurring in 3 consecutive years. Variance is additive, and if the monthly rainfall were subject to a yearly cycle the total variance could be found by estimating (1) the variance of the 50 January observations, (2) the variance of monthly means, and then adding the two together. Any other month could be used instead of January.

It is the object of this section to consider the variance of irregular variation of each type of atmospheric pollution in turn, leaving out the variance due to yearly, weekly, and daily cycles. By the method of *correlation* it is possbile to find what portion of this variance is attributable to the connexion with each meteorological element. If the correlation coefficient is r, the fraction of the variance accounted for is r^2. There is a pitfall when the effects of several meteorological elements are considered in turn. If the different elements are not independent of one another it is not fair to add together all the corresponding values of r^2. For instance, if soluble deposit is closely correlated with rainfall it will also be correlated with cloud amount, and the two values of r^2 might conceivably add up to more than 1·0, apparently covering more than the entire variance of soluble deposit. The pitfall is avoided in this case by using the partial correlation with cloud amount, rainfall being kept constant.

4·6 Irregular Variation of Deposited Matter

In any given locality the rate of deposition of pollution depends not only on the fuel consumed in that locality; it depends on rainfall, wind direction, and possibly on humidity and other meteorological factors. These conclusions can be derived from a study of the irregular month-to-month variations of deposited matter. Observations with deposit gauges in London and Glasgow in the period 1915-33 have been examined by Wilsdon.[20] He found, on analysing the irregular variation, that $\frac{1}{4}$ to $\frac{1}{3}$ of the dissolved matter was brought into the gauges by rain. The insoluble matter was affected little by rain, but was influenced by humidity and wind direction. Correlation with hours of sunshine or cloud gave no significant result. Among other points, Wilsdon suggested that more data about the direction and duration of wind should be obtained, and that the correlation between sulphur dioxide concentration and soluble deposit should be examined. The Leicester Survey was too short for a thorough statistical examination of deposited matter, although gauges had been previously maintained at two of the sites by the Leicester Health Department. The present investigation will therefore be restricted to a brief analysis for Leicester of the connections noticed by Wilsdon in London and Glasgow and to the correlation between suspended and deposited pollution.

4·61 *Deposited Matter and Wind Direction*

It was found, as Wilsdon had found, that wind direction was an important cause of variability in deposited matter. Table 4·61 gives the correlation of

17 winter months' deposits with the number of days per month when the wind was in each of 8 directions. There are 96 correlation coefficients in the table; the 14 in bold type have an accident-probability of less than 0·05, and if there were no correlation between pollution and wind direction there would be about 5 instead of 14. Nine of the fourteen significant coefficients in bold type refer to insoluble ash, and two each to insoluble combustible matter and dissolved matter. Hence there is a strong tendency for insoluble ash to depend on wind direction. There is no conclusive evidence, from Table 4·61 as it stands, that insoluble combustible matter or dissolved matter behaves similarly, but by grouping together various adjacent wind directions new significant correlations can be obtained, and it seems likely that both insoluble combustible matter and dissolved matter are influenced by wind direction, if not so strongly as insoluble ash.

The deposit gauges in Leicester were all placed as far as possible from particular factory chimneys, and yet there is evidence that more grit entered the gauges in certain winds than in others. The power station and gas works are 1¼ miles SSW of Station 1(a), and 1 mile SSE of Station 3; this may be the reason for certain of the high positive correlations in Table 4·61. In other places in Great Britain deposit gauges are placed closer to strong sources of pollution, and the variance introduced by variations of wind direction may be considerable. At such places, careful daily observations of wind direction should be made, so that the contribution of the special source may be estimated.

TABLE 4·61 *Correlation of monthly deposit with wind frequency; Winters* 1937-9.

	N	NE	E	SE	S	SW	W	NW
	Station 1(a)							
Insoluble combustible matter	−0·17	+0·29	+0·28	+0·14	−0·03	−0·10	−0·09	+0·13
Insoluble ash	**−0·64**	**−0·61**	−0·37	+0·02	**+0·58**	**+0·74**	−0·09	**−0·53**
Dissolved matter	−0·38	−0·44	−0·44	+0·39	+0·29	+0·34	+0·17	−0·43
	Station 3							
Insoluble combustible matter	−0·03	+0·30	**+0·59**	+0·25	+0·04	−0·22	**−0·48**	+0·13
Insoluble ash	−0·24	−0·38	+0·32	+0·27	**+0·64**	+0·20	−0·36	**−0·48**
Dissolved matter	−0·15	−0·06	+0·10	+0·34	−0·14	−0·11	+0·04	+0·44
	Station 7							
Insoluble combustible matter	+0·14	−0·13	+0·46	+0·45	−0·10	−0·31	−0·15	+0·39
Insoluble ash	+0·38	+0·18	**+0·72**	−0·16	−0·17	−0·49	−0·15	+0·36
Dissolved matter	+0·13	−0·24	+0·19	**+0·62**	+0·34	−0·10	−0·05	−0·40
	Station 10							
Insoluble combustible matter	−0·35	−0·38	0	**+0·52**	+0·20	+0·28	−0·20	−0·04
Insoluble ash	**−0·57**	−0·23	−0·06	−0·31	+0·19	+0·41	−0·13	−0·07
Dissolved matter	−0·32	**−0·56**	−0·14	+0·35	+0·45	+0·41	−0·11	−0·31

Note : Correlation coefficients with an accident-probability of less than 0·05 are in bold type. For Station 1(a), 17 pairs of observations were available; for Stations 3 and 10, 16 pairs; for Station 7, 14 pairs.

There are too few observations to give accurate estimates of correlation coefficients in Table 4·61. Also the wind frequencies in the eight directions are not independent of one another, and to determine the variance of deposits attributable to variance of wind direction a number of partial correlations is required. It seems likely, however, that at least half the variance of insoluble ash at Station 1(a) is attributable to wind direction.

4·62 *Variables affecting the Leicester Gauges Similarly*

These variables will produce positive correlations between the deposits at different stations. Such variables include nearly all forms of weather except

wind direction, and also many human habits, such as the seaside holiday in July or August. It is therefore important to examine the correlation between gauges; for here is a test which may immediately dispose of a large class of variables.

For 31 months during the Leicester Survey the correlation between deposits at Station 1(a) and Station 10 were: dissolved matter, +0·62; total insoluble matter, +0·22; undissolved combustible matter, +0·26. Annual variation had been eliminated. The last two correlations are not significant, and they lead to the important conclusion that there is no reason to examine any further the correlations of insoluble matter with any variable which would affect the Leicester gauges similarly.

The correlation of +0·62, on the other hand, shows that dissolved matter is influenced by one or more conditions which vary similarly at the two parts of Leicester. Rainfall is such a condition, and it is considered in Section 4·64. It is natural that rainfall should affect the two gauges similarly, either ff the clouds contain appreciable dissolved matter or if falling rain washes impurities out of the air. Another condition which affects both gauges similarly is wind direction, for Table 4·61 shows that both deposits are positively correlated with southerly winds and negatively correlated with north-easterly winds. There is insufficient material to pursue this question further, but it is interesting to note that there is no important source of pollution for thousands of miles in a north-easterly direction from Leicester.

4·63 *Humidity and State of Ground*

Wilsdon found that the insoluble deposit at Kew decreased as humidity increased, and this he suggested was because less dust was blown from the ground in moist weather. If so, there should be a positive correlation between the monthly insoluble deposit and the number of days per month when the ground is dry.

Now Section 4·62 indicates that for the 31 months considered there will not bs a significant correlation between insoluble deposit and either humidity or state of ground, at least not for *both* Stations 1(a) and 10. The inference is correct, because the correlation coefficients have been evaluated and are all numerically less than 0·3; they would not be considered significant unless they exceeded 0·35. It is to be noted that all three variables undergo yearly cycles at Leicester, and the effect of annual variation was eliminated in the calculations, to prevent spurious correlations from being found. However, there is no reason why tests on more than 31 months' observations should not give significant correlations.

From the Leicester results correlations of soluble deposits with humidity are not significant, but with state of ground are significant. However, state of ground and soluble deposits are both influenced by rainfall, and when this influence of rainfall is eliminated by partial correlation no significant connection remains.

Thus there is no evidence from the Leicester results that humidity or state of ground directly affects either the soluble or insoluble deposit.

4·64 *Rainfall*

Rainfall is more closely correlated with soluble deposit than with insoluble. Table 4·64 shows the correlation in winter (November-March) and summer (May-September) at Stations 1(a) and 10.

The investigation was not confined to the period of the Leicester Survey, and observations taken since 1925 were used. As a result, the correlation coefficients are more accurate. The squares of these correlation coefficients indicate that at Station 1(a) the variance of rainfall is responsible for 35% to 40% of the variance of dissolved matter and for 10% to 20% of the variance

TABLE 4·64 *Correlation of Monthly Deposit with Rainfall*

	No. of pairs of obs.	Correlation with rain		Regression on rain Tonnes/km.² per cm.		Percentage brought by rain	
		Insoluble Matter	Dissolved Matter	Insoluble	Dissolved	Insoluble Matter	Dissolved Matter
	Station 1(a) (Town Hall)						
Summer	60	**+0·44**	**+0·64**	+0·18	+0·16	19%	37%
Winter	64	**+0·33**	**+0·59**	+0·26	+0·20	16%	27%
	Station 10 (Humberstone)						
Summer	27	−0·18	**+0·48**	—	+0·10	—	27%
Winter	31	+0·19	+0·28	—	—	—	—

Note : Correlation coefficients with an accident-probability of 0·01 or less are in bold type. The remainder have an accident-probability greater than 0·05.

of insoluble deposit. At Station 10 the effect of rain on dissolved matter is small, and on insoluble deposit is not significant. The low correlation with rain of dissolved matter at Station 10 is surprising in view of the high correlation with dissolved matter at Station 1(a), and it is one of the clearest facts about deposits that a considerable proportion of dissolved matter is deposited only when it rains.

Columns 4 and 5 of Table 4·64 give the regression coefficients of pollution on rainfall, in the cases of significant correlation. The regression coefficients are measured in amount of deposit (as tonnes per km.²) per cm. of rainfall; for example, the value +0·20 means that if 1 cm. of rain were to fall in winter the dissolved matter in the Town Hall deposit gauge would increase on an average by the equivalent of 0·20 tonne per km.² From the regression coefficients and the average rainfall it is possible to calculate how much insoluble and dissolved matter is brought by an average month's rain. Columns 6 and 7 give the results as percentages of the total insoluble and total dissolved matter. These results may be compared with Wilsdon's values 25% and over 33% for dissolved matter in London and Glasgow respectively.

4·65 *Deposited and Suspended Sulphur*

Suspended sulphur occurs chiefly as the gas, sulphur dioxide. Particles of ash from chimneys may contain sulphur, but they remain in the atmosphere for such a short time on an average that their contribution to the sulphur content of a given volume of air may be neglected. For the present purposes, the number of parts by volume of sulphur dioxide in 100 million volumes of air will be taken to represent suspended sulphur.

Deposited sulphur occurs both in solution as sulphites and sulphates and in insoluble forms, but the sulphur content of insoluble matter is not usually estimated, because it can have little direct connection with suspended sulphur and little effect on metal articles, building materials, or plant life. The sulphur content of dissolved matter, expressed as tonnes of sulphate-ion per 100 km.² per month, will be taken to represent deposited sulphur in the present investigation.

Table 4·65 contains correlation coefficients involving deposited and suspended sulphur, total dissolved matter and other variables. Monthly means have been used throughout, and those that undergo an annual variation have been expressed as differences from the smooth curve of annual variation. In general, considerably more data were used for estimating annual variations than were used in Table 4·65, so there was no reduction in the number of degrees of freedom in the calculation.

Rows 1, 2, 3 of Table 4·65 show how closely the irregular monthly variations at four stations go together. Apart from suspended sulphur at Station 7, in a country district with no industrial activity, the correlations are all significant, varying between +0·47 and +0·72. They show therefore that from 25% to 50% of the variance is due to causes which affect the four stations similarly.

TABLE 4·65 *Correlations with Deposited and Suspended Sulphur*

Row No.		Stn. 1(a)	Stn. 3	Stn. 7	Stn. 10
	No. of complete months' records	36	24	24	20
	Correlation with same variable at Station 1(a), for:				
1	total dissolved matter	+1·0	**+0·47**	**+0·54**	**+0·72**
2	sulphate deposit	+1·0	**+0·66**	**+0·61**	**+0·48**
3	suspended SO_2	+1·0	**+0·53**	+0·11	**+0·54**
	Correlation of monthly rainfall with:				
4	total dissolved matter	**+0·72**	**+0·55**	**+0·73**	**+0·57**
5	sulphate deposit	**+0·74**	**+0·70**	**+0·54**	+0·17
6	suspended SO_2	**−0·36**	−0·10	−0·11	−0·07
	Correlation of mean early-morning temperature gradient with:				
7	total dissolved matter	−0·20	−0·14	−0·03	−0·23
8	sulphate deposit	−0·21	−0·27	−0·01	+0·24
9	suspended SO_2	**+0·33**	+0·38	+0·27	+0·42
	Correlation of mean wind velocity with:				
10	total dissolved matter	−0·08	−0·22	−0·36	−0·09
11	sulphate deposit	−0·14	−0·29	−0·07	−0·36
12	suspended SO_2	−0·16	−0·38	+0·29	−0·29
	Correlation of frequency of N, NW, W, SW winds with:				
13	total dissolved matter	−0·18	−0·37	**−0·40**	0·00
14	sulphate deposit	−0·31	**−0·59**	−0·34	−0·08
15	suspended SO_2	+0·10	−0·34	−0·03	+0·09
	Correlation of:				
16	dissd. matter and sulphate deposit	**+0·58**	**+0·78**	**+0·60**	**+0·59**
17	sulphate deposit and suspended SO_2	−0·19	−0·05	+0·26	**+0·73**
18	suspended SO_2 and total dissd. matter	−0·29	−0·29	+0·05	+0·35

Note : Correlation coefficients within the 5% significance level—i.e. having an accident-probability of 0·05 or less—are in bold type.

Rows 4, 5, 6 show that total dissolved matter and sulphate deposit are usually correlated with rainfall; hence rainfall might cause the common part of the variance of these variables. The partial correlation coefficients with the same variable at Station 1(a), keeping rainfall constant, are:

	Stn. 3	Stn. 7	Stn. 10
Total dissolved matter	+0·12	+0·03	**+0·54**
Sulphate deposit	+0·29	+0·37	**+0·53**

The partial correlations with Stations 3 and 7 are no longer significant, and therefore rainfall may be the only factor tending to cause similar irregularities in the deposits in the four Leicester stations as a whole. The partial correlations between Stations 1(a) and 10 remain significant, however. Evidently rainfall is not the only factor common to the gauges at Stations 1(a) and 10, but the other common factors, whatever they may be, are not common to all the Leicester gauges.

One such factor appears to be the frequency of different winds. In Table 4·61 the correlations for Stations 1(a) and 10, particularly for dissolved matter, are very similar. For winter, the correlations of dissolved matter with frequency of

winds from the octants SE, S, and SW are: Station 1(a), **+0·25**; Station 3 −0·04; Station 7, +0·22; Station 10, **+0·58**. It will be noted that only the first and last of these are significant. If the frequency of southerly winds is kept constant, the correlation of dissolved matter at Stations 1(a) and 10 diminishes from +0·72 to +0·60. A further reduction would occur if other wind directions were treated similarly, but there are insufficient data to make a satisfactory investigation of this subject. It seems likely from the available evidence, however, that the correlation between soluble deposits at Stations 1(a) and 10 is high, even when rainfall is kept constant, because almost any change of wind direction has a similar effect at the two stations.

In row 9 of Table 4·65, there is some evidence of correlation between suspended sulphur and temperature gradient, high concentrations of sulphur dioxide occurring when the air is warmer at 1,000 ft. than at the ground. This correlation is investigated again in Section 4·521.

Rows 13, 14, and 15 are included in Table 4·65 because appreciable amounts of soluble matter might be blown from the Midland industrial districts in N, NW, W and SW winds, but, instead of increasing pollution at the four Leicester stations, these winds tend to cause a decrease.

In row 16, the correlations between sulphate deposit and dissolved matter are high, as might be expected since sulphates often form as much as half the total dissolved matter in deposit gauges. In rows 17 and 18 the only significant correlation between deposited and suspended sulphur is +0·73 at Station 10. For confirmation, the correlation between deposited sulphur and the yield of sulphate by the lead peroxide method at station 10 was calculated. It was +0·36 for 36 months, lower than +0·73, but still significant. There appears to be some special reason at Station 10 for deposited and suspended sulphur to be correlated, but there is nothing in Table 4·515 or in the remainder of this investigation to show what the reason is. Row 18 suggests that suspended sulphur has little connection with total dissolved matter at Station 10: the correlation seems to be only with sulphate deposit. At other stations, rows 17 and 18 show no connection between suspended sulphur and sulphate or other soluble deposit. This supports the suggestion in Section 4·64 that the rain-brought part of soluble deposits comes mainly from clouds. If falling rain washed sulphur dioxide out of the lower atmosphere, high concentrations of sulphur dioxide would be associated with heavy deposits; unless the washing process were so rapid that concentrations of sulphur dioxide were appreciably reduced, in which case the correlation would be negative. What evidence there is supports the view that neither falling rain nor the action of clouds reduces concentrations of sulphur dioxide at all rapidly.

4·66 *Deposited and Suspended Combustible Matter*

By combustible matter in deposit gauges will be meant the tar and loss on ignition of the insoluble matter; soluble loss on ignition is liable to be misleading, and is not normally measured. It was pointed out in Section 2·321 that about 31% of deposited matter was combustible in this sense. Of suspended matter collected by the smoke filter, about 85% was combustible, and the photometric method of measuring the smoke stains tends to give more weight to sooty matter than to ash, which is usually lighter in colour. For the present purposes, therefore, smoke will be regarded as synonymous with suspended combustible matter.

Table 4·66 contains correlation coefficients involving deposited and suspended combustible matter and other variables. The data were treated in the same way as for Table 4·65. In row 1 the correlations are low, and there is thus little reason for expecting combustible deposit to be significantly correlated with any variables which affect all districts similarly. Rows 3, 5, 7 and 9 bear out this conclusion, for there are no

TABLE 4·66 *Correlations with Deposited and Suspended Combustible Matter*

Row No.		Stn. 1(a)	Stn. 3	Stn. 7	Stn. 10
	No. of complete months' records	35	24	22	20
	Correlation with same variable at Station 1(a), for:				
1	combustible deposit	+1·0	**+0·41**	+0·20	+0·09
2	suspended smoke	+1·0	**+0·63**	**+0·61**	**+0·60**
	Correlation of monthly rainfall with:				
3	combustible deposit	+0·31	+0·20	+0·18	+0·30
4	suspended smoke	−0·19	−0·19	−0·06	−0·10
	Correlation of mean early-morning temperature gradient with:				
5	combustible deposit	−0·11	−0·34	−0·26	**−0·55**
6	suspended smoke	+0·07	+0·23	−0·08	+0·35
	Correlation of mean wind velocity with:				
7	combustible deposit	−0·27	−0·34	**−0·61**	−0·29
8	suspended smoke	−0·17	**−0·49**	**−0·54**	−0·13
	Correlation of frequency of N, NW, W, SW winds with:				
9	combustible deposit	−0·25	−0·09	−0·36	−0·11
10	suspended smoke	+0·04	−0·11	+0·17	+0·21
	Correlation of combustible deposit with:				
11	suspended smoke	−0·03	+0·15	+0·26	+0·16

Note : Correlation coefficients within the 5% significance level—i.e. having an accident-probability of 0·05 or less—are in bold type.

significant correlations with rainfall or wind from the industrial Midlands, and only one with temperature gradient and one with wind velocity. Many more observations would be needed before such correlations could be definitely established.

The high correlations in row 2 show that 35% to 40% of the variance of monthly mean smoke concentration is due to causes which affect the four stations similarly. Rows 4, 6, 8 and 10 provide little evidence of what these causes are, but suggest that one of them may be wind velocity. However, the method of correlating monthly means is not the best way of investigating the variance of smoke concentration. A method using weekday means is used in Section 4·521, and this gives more conclusive results.

In row 11, there are no significant correlations between suspended smoke and combustible deposit.

4·67 *Irregular Variation of Deposited Matter—Summary*

The Leicester Survey was not planned to yield the maximum information about deposited matter, because it was considered more important to investigate the distribution and general behaviour of smoke and sulphur dioxide. Moreover, monthly observations are not the best type of data for correlating with variables which may alter considerably from day to day and during the day, but which are less erratic over longer periods. Owing to the large changes within each month, it is unlikely that any close correlation would be found in monthly data, especially after the effect of yearly cycles has been eliminated. In general, results for deposited matter in Leicester are similar to Wilsdon's conclusions for London and Glasgow (Section 4·6). It was found in Leicester that:

(1) Insoluble ash depends fairly strongly on wind direction; dissolved matter and soot less strongly.

(2) Up to 40% of the dissolved matter in an average month is brought into the gauges by rain; the effect of rain on insoluble matter can only be detected at Station 1(a), where 124 months' observations were available since 1925.

(3) Apart from rain, there is no evidence that deposited matter was influenced by any variable affecting all the Leicester gauges similarly: humidity, state of ground, temperature gradient and wind velocity are such variables, and their influence cannot be considered as satisfactorily established at Leicester.

The evidence of Section 4·6 as a whole suggests that much of the matter collected in deposit gauges may be of extremely local origin. This could be verified by making a statistical experiment, but the investigation would be elaborate and costly, probably involving from 2 to 5 years' observations with about 30 deposit gauges. A less clumsy experiment would be possible if deposits could be collected and analysed more rapidly, but no satisfactory improvement of this nature has been devised.

4·7 Irregular Variation of Suspended Matter

Day-to-day variations in smoke in the central districts of a city are obvious enough to the casual observer. They are shown in this section to be mainly due to day-to-day variations in turbulence, temperature, and rainfall. In the centre of Leicester, and presumably in other large polluted areas, the concentration of smoke is not strongly influenced by wind; but in the suburbs it is influenced by both wind force and direction (see figures 3·48). Similar conclusions apply to pollution by sulphur dioxide.

The daily mean concentration of smoke and sulphur dioxide was observed in Leicester every day for three years. Although the 15 stations were not all in use at the same time, a considerable mass of observations was accumulated. Daily or hourly readings were also obtained of meteorological data which were thought likely to have some bearing on the very great day-to-day variation which suspended impurity was known to undergo. Many of these data were provided by the meteorological station, which was specially set up by the Leicester Health Department at the City General Hospital (Station 9). In addition to the normal climatological observations of temperature, pressure, rainfall, humidity and general weather conditions, this station kept records of sunshine, grass minimum temperature and earth temperature, and also continuous records of temperature, pressure, and humidity. Most important of all from the point of view of the Leicester Survey were the continuous records of wind velocity and direction obtained with a Dines pressure tube anemometer, with a vane 40 ft. above the ground.

The meteorological station began observations in June, 1937, 5 months after the Leicester Survey began. Smaller stations had previously been in operation at Hinckley and at the City Mental Hospital (Station 10), and their records provided some of the required observations for the missing 5 months. The only important observations still required were a suitable measure of atmospheric turbulence, and for these it was necessary to use observations of vertical temperature gradient, made each weekday on an aeroplane ascent from Mildenhall, usually between 6 and 7 a.m. The temperature increase in degrees Fahrenheit between the ground and 1,000 ft. was used as a measure of turbulence. It varied from -7 on very turbulent days to $+19$ on days of little or no vertical air exchange. Mildenhall is 70 miles east of Leicester, and it is not known how much conditions differ over the two places, but the standard deviation of temperature gradient between Mildenhall and other places about 400 miles away was found to be ± 4°F. per 1,000 ft. If the variance is proportional to the distance apart, it follows that the standard deviation between Mildenhall and Leicester would be ± 1 to 2° F. per 1,000 ft., and this is not a serious error.

It is common in the early morning for there to be an inversion near the ground, the temperature increasing upwards so that the temperature gradient is positive. This often happens in fairly cloudless weather, and the early-morning inversion then tends to be matched by an equally strong negative temperature gradient in the middle of the day. For this reason, early-morning temperature gradients at Mildenhall must tend to be positively correlated with morning and evening pollution but negatively in the afternoon. The balance turns out to be a positive correlation, especially for smoke, which has a pronounced morning maximum.

Throughout 1939, temperature gradient near the ground at Station 9 was observed hourly, by an apparatus recording the difference in temperature between thermocouples at 17 ft. and 32 ft. 2 in. above the ground. From May to December, 1939, the hourly wind run of two cup anemometers in the same positions as the thermocouples was recorded. This was done because rate of change of wind velocity with height is also connected with turbulence. Lastly, from June to December, 1939, visual observations on the smoke trail from a suitable chimney were made on weekdays at 9 a.m. The shape of the curve enveloping the smoke trail should theoretically depend on the turbulence and velocity of the air in the region of the chimney. It was hoped that these observations might lead to a convenient method of estimating turbulence, in case daily observations of turbulence should be desirable in association with routine measurements of atmospheric pollution.

4·71 *Dependence on Wind Velocity and Temperature Gradient*

There are three points to consider before the daily mean concentrations of smoke and sulphur dioxide can be examined for dependence on wind velocity and temperature gradient. The first is to eliminate the effect of varying wind direction, since the west end of a town, for instance, is more polluted in east winds than west winds. It is desirable, therefore, to work with the records of a station or a group of stations so placed that wind direction does not affect their mean pollution. The most convenient group of this nature consists of Stations 1, 2, 3, and 4, and the mean of the daily mean concentrations at these stations is used throughout the present section. It will be described as the pollution in Central Leicester. There was usually from 30% to 50% more smoke at Station 1 than at Stations 2, 3, and 4, and between two and three times as much sulphur dioxide. It might be argued that for this reason Station 1 should be omitted from the group, at any rate when discussing sulphur dioxide, but it is an advantage to consider an area rather than a ring, and there are no mathematical reasons for excluding Station 1. It is sufficient to note that nearly half the variance of sulphur dioxide in Central Leicester is attributable to Station 1. The chief advantage of using a group of stations, rather than a single station, is that it reduces the influence of variations in pollution due to local fires such as rubbish burning or smoky chimneys.

The second task is to eliminate the effects of periodic variations. The methods of doing this were enumerated in Section 4·5. In view of the weekly cycle of pollution, and the small number of Sunday observations of temperature gradient, Sunday readings have been omitted from this discussion. The yearly cycle of pollution is eliminated by expressing each daily mean concentration in Central Leicester as the ratio to its normal value. Normal value is defined as the value in zero temperature gradient and in a wind of about 7 m.p.h. It was calculated monthly from a group of days whose mean wind velocity was between 3 and 10 m.p.h. inclusive, and whose mean temperature gradient was zero. The method of selection was quite automatic, and the monthly groups usually contained 10 to 20 days. The normal values of smoke and sulphur dioxide are plotted in Fig. 4·71(a). They do not differ much from the yearly cycles of Fig. 4·21; but this result could not have been anticipated, because the

extremely different daily cycle of turbulence at different seasons might have seriously affected the yearly cycle of pollution. The principal difference from Fig. 4·21 is that the winter maximum has moved from mid-December to mid-January. There is also an appreciable reduction in the scatter of the monthly means from the smooth curves.

The daily cycle of pollution (Fig. 4·41) is eliminated by using daily mean observations, but it does not follow that temperature gradient should be averaged in the same way. During the night, when little pollution is emitted,

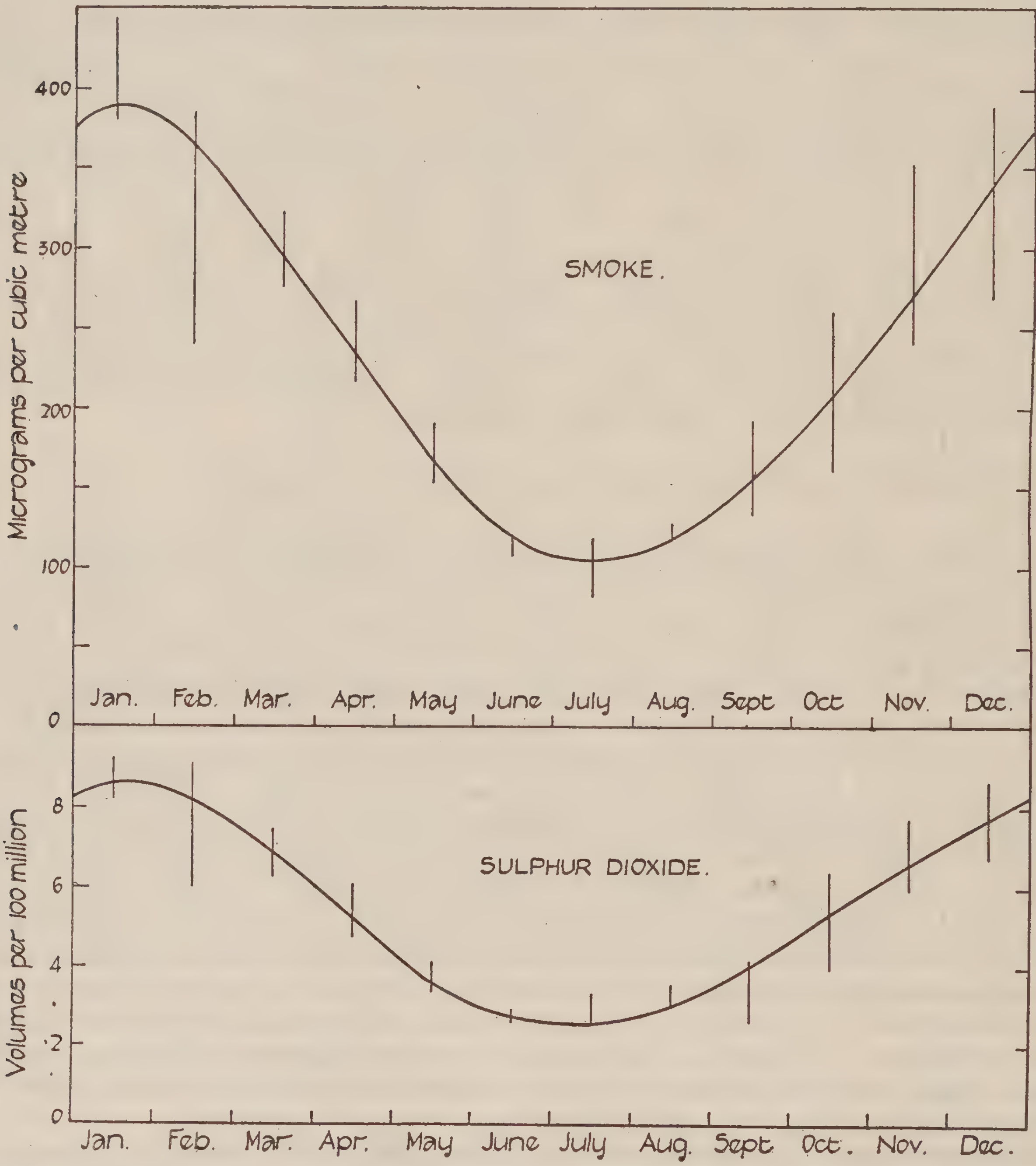


Fig. 4·71(a) Yearly Cycle in Central Leicester on Days of Zero Lapse Rate and Moderate Winds.

it is relatively unimportant whether pollution is retained near the ground or not. Evidently the temperature gradient at each hour of the day should be multiplied by a weighting factor proportional to the normal rate of emission of pollution at that hour, and the weighted average taken. The requisite data for this treatment are not available, and it is necessary, for the greater part of the period of the survey, to use single daily observations of temperature gradient at about 6 to 7 h. at Mildenhall. Using observations at Mildenhall instead of Leicester adds to the variance of temperature gradient a small term which cannot be correlated with the pollution at Leicester. Using a single

observation instead of a weighted daily mean adds a similar term, but, beyond saying that it may be rather large, no estimate of its magnitude can be made. The effect of this is to mask the dependence, if any, of pollution on temperature

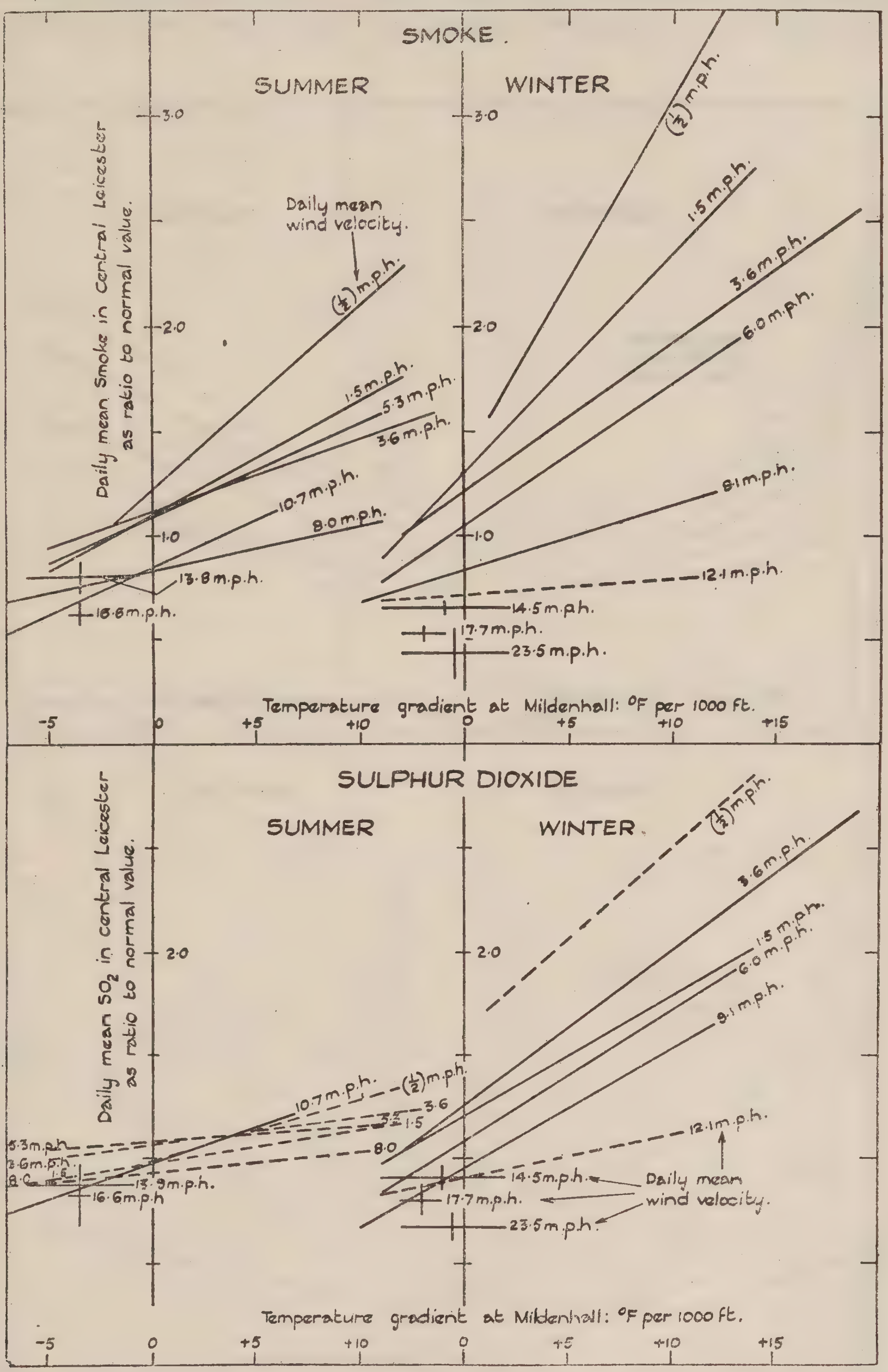


FIG. 4·71(b) REGRESSION OF SUSPENDED IMPURITY ON TEMPERATURE GRADIENT AT CONSTANT WIND VELOCITIES.

Note: The length of each line is determined by the range of temperature gradients for which observations are available. When the regression is not 5% significantly different from zero, a broken line is used; or else the regression line has been drawn horizontally with a short vertical line to represent the standard error of the mean.

gradient, and the dependence must also be masked by the tendency for temperature gradient to have an exceptionally strong daily cycle in certain weathers (referred to in Section 4·52). However, it will transpire that, even so, the dependence is quite clear and significant. There are similar difficulties in the way of treating wind velocity, but since hourly observations were available the

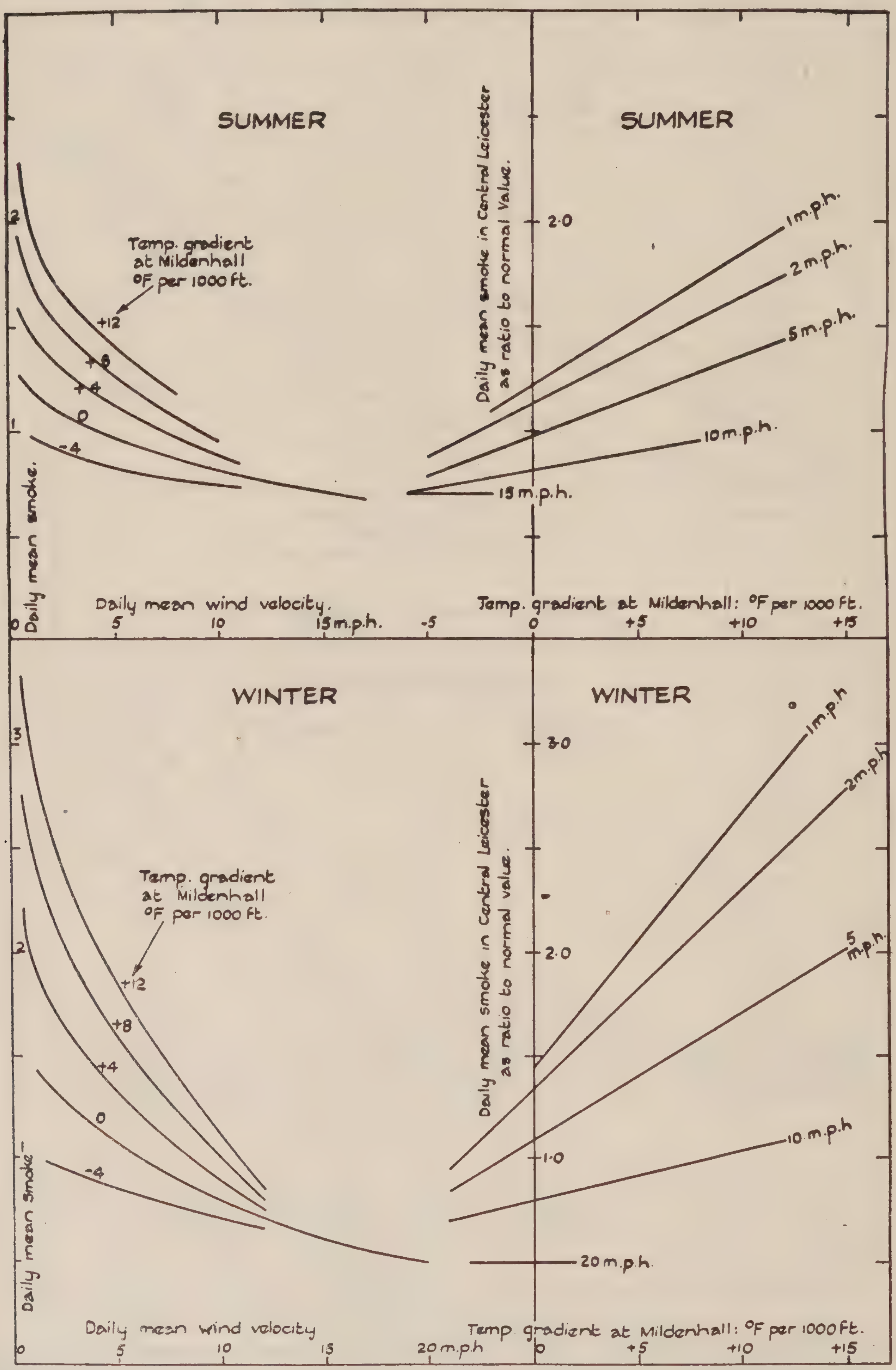


Fig. 4·71(c) Dependence of Smoke on Wind Velocity and Temperature Gradient.

unweighted daily mean was used, rather than a single daily observation. Both temperature gradient and wind velocity, therefore, will appear to be less closely connected with pollution than they really are; estimates of correlation coefficients will be lower and tests of significance less positive than they might have been. There is no reason to suppose, however, that the degree of de-

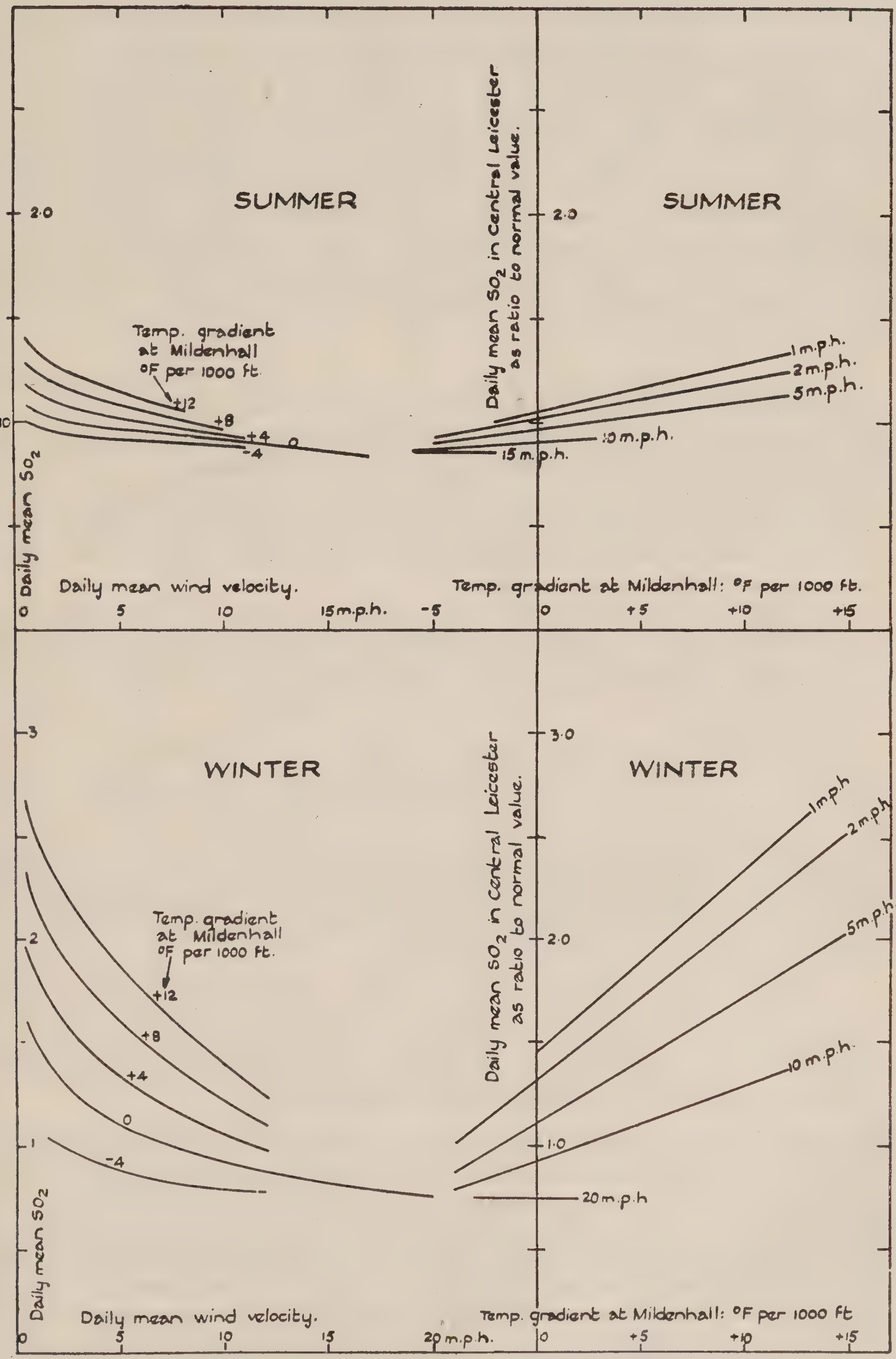


FIG. 4·71(d) DEPENDENCE OF SULPHUR DIOXIDE ON WIND VELOCITY AND TEMPERATURE GRADIENT.

pendence will be falsely estimated; estimates of regression coefficients are equally likely to be high or low, although they are bound to be reduced in accuracy by the treatment of daily means.

The final matter is to consider whether the dependence to be examined is likely to be linear. The amount of air brought per second to each chimney top is proportional to the wind velocity u, so that the smoke produced in one second is immediately distributed in a volume proportional to u. Hence it would be reasonable to expect a linear relation between the concentration of pollution and $1/u$. It will be shown, however, that this relation is not obeyed in Central Leicester, and an explanation will be given in Section 4·711. Nevertheless, the data must evidently be considered in groups for which the range of wind velocity is small. It would be wrong, for instance, to calculate the best linear regression of pollution on wind velocity for the whole range of observed wind velocities. It is particularly convenient, therefore, that the relation between pollution and temperature gradient is not distinguishable from a straight line. This can be demonstrated by statistical tests, and it leads to a fairly simple way of examining the data, by finding the regression of pollution on temperature gradient, for various values of wind velocity. The entire proceedure is as follows:

1. Find the mean for each weekday of the daily mean concentrations of pollution at Stations 1, 2, 3, and 4. Find the mean wind velocity during the same 24 hours (usually the records were changed at 16-20 h.). Note the earlier morning temperature gradient at Mildenhall.
2. Month by month, collect days of mean wind velocity between 3 and 10 m.p.h., inclusive, into groups whose mean temperature gradient is zero. Plot the mean pollution of such groups as yearly cycles of the "normal value" of pollution (Fig. 4·71(a)).
3. Express each daily mean of pollution as a ratio to the normal value.
4. Divide the days into (a) summer (May to September) and winter (November to March); (b) days of mean wind velocity less than 1 m.p.h., 1 to 2 m.p.h., 3 to 4 m.p.h., 5 to 7 m.p.h., and so on. The total number of groups is 18.
5. For each group calculate the regression of pollution (from step 3) on temperature gradient—it will be noted that temperature gradient is allowed to vary freely within each group. Plot the results as in Fig. 4·71(b).
6. Read off from Fig. 4·71(b) the most probable value of smoke or sulphur dioxide at certain wind velocities and temperature gradients. Plot these readings against wind velocity as abscissæ, drawing the best group of smooth curves through the plotted points. This is done on the left-hand sides of Figs. 4·71 (c) and (d).
7. Re-plot the group of smooth curves against temperature gradient as abscissæ, drawing the best group of straight lines through the plotted points. This is done on the right-hand sides of Figs. 4·71 (c) and (d). The only difference from Fig. 4·71(b) is that proper weight has been given to neighbouring lines in drawing each regression line.

Figs. 4·71 (c) and (d) show the dependence of smoke and sulphur dioxide on wind and temperature gradient. They depict an entirely new result, and they deserve some consideration. Firstly it is evident that sulphur dioxide is less affected than smoke by either wind velocity or temperature gradient. One possible explanation of this result depends on the difference in the daily cycle of smoke and sulphur dioxide between 6 a.m. and 11 a.m., shown in Fig. 4·41. Since there is relatively more smoke at this time of day, it is reasonable that the mean daily smoke concentration should be more dependent than sulphur dioxide on the early-morning temperature gradient. Another reason may be because relatively more smoke than sulphur dioxide is emitted from domestic

chimneys. On days of high positive temperature gradient, pollution from high industrial chimneys may not reach the ground in the first mile or so of its travel. The same effect may occur on days of low wind velocity, when little turbulence can be produced by the wind.

The figures also make it clear that the dependence of suspended impurity on both wind velocity and temperature gradient is closer in winter than in summer. This may be connected with the different origin of the pollution in the different seasons, both kinds of pollution, and more particularly sulphur dioxide, being more industrial in origin in summer than in winter. It was suggested above that the pollution from high industrial chimneys may travel a mile or more on stable days on high positive temperature gradient before any of it reaches the ground. The mean height of the volumetric sulphur dioxide and smoke apparatus at the four central stations was 20 ft. above the ground, or about 100 ft. below the tops of industrial chimneys. If the truth of this suggestion could be established, it would be an additional argument in favour of tall industrial chimneys; for although a taller chimney would not reduce the total atmospheric pollution it would help to reduce the maximum concentration of pollution near the ground. A theoretical discussion of the spread of smoke and gases from chimneys has been given by C. H. Bosanquet and J. L. Pearson.[25]

4·711 *Empirical formulæ*. The regression lines of each quarter of Fig. 4·71(b) may be expressed approximately by a single empirical formula containing three constants. If P represents the daily mean pollution as ratio to its normal value, u the daily mean wind velocity in m.p.h., and L the early-morning temperature gradient at Mildenhall in °F. per 1000 ft., the formulæ are:

$$\left.\begin{array}{ll} \text{Smoke, summer:} & P = 0{\cdot}7 + \dfrac{0{\cdot}07}{u^{0\cdot4}}\,(8+L) \\[2ex] \text{Smoke, winter:} & P = 0{\cdot}6 + \dfrac{0{\cdot}15}{u^{0\cdot7}}\,(8+L) \\[2ex] SO_2\text{, summer:} & P = 0{\cdot}9 + \dfrac{0{\cdot}02}{u^{0\cdot4}}\,(9+L) \\[2ex] SO_2\text{, winter:} & P = 0{\cdot}6 + \dfrac{0{\cdot}10}{u^{0\cdot5}}\,(9+L) \end{array}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

It seems probable that the powers of u and the numbers bracketed with L should be the same in all four equations. In addition, P should be 1·0 when $L=0$ and $u=7$ m.p.h. Using these simplifications, the four equations can be re-expressed approximately so as to differ from one another in the value of a single constant, by

$$\left.\begin{array}{l} P = 1 - 3{\cdot}2a + \dfrac{a}{\sqrt{u}}\,(8{\cdot}5+L) \\[2ex] \text{where } a = 0{\cdot}08 \text{ for smoke, summer} \\ \qquad\; a = 0{\cdot}14 \text{ for smoke, winter} \\ \qquad\; a = 0{\cdot}025 \text{ for } SO_2\text{, summer} \\ \qquad\; a = 0{\cdot}11 \text{ for } SO_2\text{, winter} \end{array}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Equation (2) seems to be the best algebraical way of expressing the dependence of suspended pollution on wind velocity and temperature gradient, taking all the available data into consideration. It is surprising in two ways, in that a is variable and in that u is less important than might be expected, occurring only to the power $-\frac{1}{2}$.

The value of a seems to be connected with the average height above ground at which the pollution is emitted. Thus in summer, when most of the sulphur

dioxide in Leicester is probably emitted from factory chimneys, the value of a for sulphur dioxide is very small. For smoke, in winter, when most of the smoke is produced by domestic chimneys, a is about 5 times as large. The other two values of a are intermediate, and occur in circumstances when the emission of pollution is less definitely industrial or domestic. The variability of a seems therefore to be because when the chimneys are high some turbulence will be necessary before their pollution can reach the ground. Whether this is the complete explanation seems doubtful, however. It was noted in Section 4·211 that the irregular variations of monthly means is less, proportionally, in summer than in winter. This appears to be connected with the yearly cycle of a, and it is difficult to believe that the explanation given above will account for so large an effect.

The power of u in equation (2) may be due to the direct effect of wind on concentration of pollution. But it is known that (a) pollution decreases with increasing turbulence, (b) turbulence at all heights increases with increasing wind velocity at any one given height, and it is suspected that (c) although temperature gradient is kept constant in the left-hand curves of Fig. 4·71(c) the variations of turbulence due to variations of wind velocity have not been eliminated. Therefore the power of u in equation (2) may be partly due to the correlation between u and turbulence, and if turbulence were kept constant the concentration of pollution might be found to be more nearly independent of u. There is reason to believe, from theoretical considerations, that, in a sufficiently large uniform town, pollution should be independent of wind velocity.

Equation (2) is a practical result which has not yet been completely justified by theory, and there is scope for considerable research on the mechanism whereby pollution in the atmosphere is diluted by cleaner air.

4·72 *Best Way of Estimating Turbulence*

No exact definition of turbulence has yet been made, but the word has been used, in this report and elsewhere, to describe the readiness with which air mixes with itself. During the last nine months of the Leicester Survey, special attention was given to the measurement of variables connected with turbulence, because of the importance of turbulence in determining the concentration of suspended pollution. It was thought that one of these variables might prove suitable for more general use in connection with measurements of atmospheric pollution.

The first test of whether a variable is suitable for general use as an indicator of turbulence must be its correlation with smoke and sulphur dioxide, but speed and convenience of measurement may also be considered. Correlation coefficients are given in Table 4·72. They were determined from observations taken during October, November and December, 1939. As nearly as possible the same group of weekdays was used for each correlation. Daily mean observations of pollution were used, so the test is for measures of daily mean turbulence rather than instantanteous values. Annual variations were eliminated.

The first co-variable of daily mean pollution in the table is the early-morning temperature gradient at Mildenhall. This was found by taking the difference between thermometer readings at ground level and at 1000 ft. A balloon or aeroplane is an essential part of the equipment for this measurement.

The second co-variable is daily mean temperature gradient at the City General Hospital, Leicester. This required two sensitive thermometers suitably housed on a 30-ft. mast, with recording equipment. It is probable that a single observation of the temperature gradient would have been nearly as well correlated, and the need for recording equipment would then be eliminated. It might be that the duration of an inversion is more important than its intensity for deciding the daily mean pollution. For this reason, the number of hours of inversion per day was also examined (see row 2a).

TABLE 4·72 *Correlations with Nine Daily Measures of Turbulence*

	No. of obs.	Correlation with daily mean	
		Smoke	SO_2
1. Early morning temp. gradient (at Mildenhall)	57	**+0·33**	**+0·28**
2. Daily mean temp. gradient	57	**+0·35**	**+0·29**
2a. No. of hours when the temp. gradient near the ground was positive	57	**+0·26**	+0·12
3. Daily mean wind gradient (as velocity difference)	52	**−0·42**	**−0·35**
3a. Daily mean wind gradient (as velocity ratio) . .	52	+0·27	+0·09
4. Log (median Richardson's number)	43	**+0·42**	+0·29
4a. No. of hours when R_i was not less than $\frac{1}{2}$ . .	43	**+0·62**	**+0·45**
5. Log (eddy diffusivity at 9 h.) from chimney observations	57	**−0·43**	**−0·49**
6. Soil temp. at 1 ft. depth *minus* grass minimum	57	**+0·48**	**+0·39**

Note : Correlation coefficients within the 5% significance level—i.e. having an accident-probability of 0·05 or less—are in bold type.

The third co-variable is daily mean wind velocity gradient at the City General Hospital, Leicester. This was measured with two cup anemometers on a 30-ft. mast. Simple wind velocity can be considered as a measure of turbulence, as in the last section, but wind velocity gradient is more fundamental.

The fourth co-variable is Richardson's number, in the form *log* (*median* R^i). Estimation of this number is complicated, involving two recording thermometers and two recording cup anemometers on a 30-ft. mast. The method was described in Section 4·42. Since Richardson's number is a criterion of whether or not the air is stable, the number of hours when R_i exceeded the critical value was also examined.

The fifth co-variable is eddy-diffusivity, which is described for instance by Brunt.[23] A convenient way of measuring eddy-diffusivity at chimney level may be developed from a theoretical discussion by O. F. T. Roberts.[26] The average outline of the smoke trail from a chimney, when viewed laterally, is given approximately by

$$z^2 = \frac{2Kp}{u}\left(\log \frac{q^2}{4\ KuN^2} - \log \rho\right) \qquad (1)$$

where z is the vertical distance above the level of the chimney top,
ρ is the vectorial distance from the chimney top,
K is the eddy-diffusivity,* defined by the differential equation

$$\frac{\partial P}{\partial t} = \frac{K\partial^2 P}{\partial z^2}$$

u is the wind velocity,
q is the rate of emission of smoke,
N is the mass of smoke per square foot which is just visible.

In equation (1), when $\rho = o$, $z = o$: i.e. at the chimney top, the width of the smoke trail is zero. Again when $\rho = q^2/4\pi KuN^2$, $z = o$: this value of ρ is the maximum distance from the chimney at which the smoke trail is visible, and, since it is observable, may be given a special symbol $\rho^{\max}$. Equation (1) may then be written

$$z^2 = \frac{2K\rho}{u} \log \frac{\rho^{\max}}{\rho}$$

All the quantities in this equation except K can be measured directly, so that K can be determined.

* In practice, K is found to be non-isometric, and, like u, to increase upwards. Moreover, it has been found that K increases rapidly with the scale of the phenomena.[32] It is not to be expected, therefore, that K is a perfect measure of turbulence as it affects pollution.

Observations were made daily at 9 h. G.M.T. on the smoke trail from the chimney of the Abbey Pumping Station (Station 4). This chimney, 162 ft. high, was well isolated and the smoke could be observed laterally from a suitable distance, whatever the direction of the wind. It was convenient to observe the width of the smoke trail at one chimney length from the top of the chimney, and the total length of the smoke trail was also measured in chimney lengths. Wind velocity u was estimated by the Beaufort scale. One set of observations and the calculation of K required about 10 minutes.

The sixth co-variable can be abstracted from the records of climatological stations. Since it is accepted that turbulence is inhibited on nights when the ground cools rapidly, the rate of cooling at the ground must be a measure of turbulence. A measure of this rate of cooling may be obtained by subtracting the grass minimum temperature from the soil temperature one foot below the surface.

In Table 4·72 the correlation coefficients, without regard to sign, may be used to compare the different methods of estimating turbulence. The standard error (using the term loosely) of each correlation coefficient is about 0·1, and none is significantly higher than the rest. As far as can be judged from the table, method 4(a) is likely to be the best. It is almost certainly better to treat Richardson's number as a criterion (method 4(a)) than as a measure (method 4). Methods 5 and 6 also commend themselves, both because of their high correlations and the ease with which the necessary measurements and calculations are made.

4·73 *Correlation between Smoke and Sulphur Dioxide*

In Section 4·71, the two co-variables of turbulence, (a) wind velocity and (b) temperature gradient, were shown to have similar but not identical effects on the concentrations of smoke and sulphur dioxide. In order to consider whether there are other variables affecting both kinds of suspended pollution similarly, the correlations between smoke and sulphur dioxide were prepared for Table 4·73.

TABLE 4·73 *Correlations of Daily Smoke with Sulphur Dioxide in Central Leicester*

Temp. grad. at Mildenhall °F./1000 ft.	No. of obs.	Correlation coefficient	Variance		Residual Variance	
			Smoke	SO_2	Smoke	SO_2
April-September						
<0	182	**+0·41**	14	10	12	9
0 to +4	153	**+0·50**	16	14	12	11
>4	86	**+0·45**	31	16	25	13
October-March						
<0	144	**+0·37**	8	7	7	6
0 to +4	134	**+0·74**	36	15	16	7
+5 to +10	63	**+0·75**	88	30	39	13
> +10	28	**+0·65**	58	41	34	24

Note : Variance is expressed as $100 \times \left(\frac{\text{difference from mean}}{\text{mean}}\right)^2$. Residual variance is the portion which is not attributable to causes common to smoke and sulphur dioxide.

It had been found from correlations month by month that there was a marked decrease in March or April and a similar increase in October; so two seasons of five months each were considered. By dividing each season into groups of

days on which the early-morning temperature gradients at Mildenhall were similar, it was found that:—

(a) In April-September, there was no appreciable variation of correlation with temperature gradient: smoke but not sulphur dioxide was significantly more variable in positive than in negative temperature gradients.

(b) In October-March, correlation was significantly higher in positive than in negative temperature gradients, and so was the variance of both smoke and sulphur dioxide. In inversions smoke was significantly more variable than sulphur dioxide.

(c) During inversions, smoke was significantly more variable in winter than in summer. The same was true for sulphur dioxide in strong inversions.

These conclusions may be checked from Table 4·73, in which the standard error of a correlation coefficient is 0·1 to 0·2, and of a variance is 2 to 4.

The square of a correlation coefficient is the fraction of the variance due to factors which act alike on both variables. From the squares of the coefficients in Table 4·73, there is no reason to expect more than about 0·6 of the variance of smoke and sulphur dioxide to be a common property. By the same reasoning there are correlation coefficients in Table 4·72 which are high enough to suggest that, of this 0·6, at least 0·3 is due to turbulence; and, since none of the measures of turbulence was ideal, 0·3 is likely to be considerably less than the true value.

The residual variance, which cannot be attributed to causes operating similarly on smoke and sulphur dioxide, is given in the right-hand columns of Table 4·73. Causes of this residual variance may include:

(1) differences in rate of emission, which are to be expected because smoke is produced by inefficient combustion whereas sulphur dioxide is always present in the flue gases from solid fuels;
(2) differences in height of emission, for proportionately more sulphur dioxide than smoke is emitted from industrial chimneys;
(3) differences in place of emission; the sources of sulphur dioxide are generally closer to the centre of Leicester;
(4) different rates of removal; for instance, sulphur dioxide may be removed by reaction with ammonia and smoke by collision with vegetation and other obstructions near the ground;
(5) casual errors of observation; these are negligible in the case of sulphur dioxide, but for smoke they are responsible for a variance of about 2 in the units of Table 4·73;
(6) casual errors in the process of eliminating the effects of annual variation.

Of the above possibilities, that of different rates of removal is considered in Section 5·23. It is there found that smoke is probably removed faster than sulphur dioxide, but both rates of removal are so slow that only country pollution can be much affected. It seems that the main causes of independent variations of smoke and sulphur dioxide are connected with the difference between domestic and industrial combustion of solid fuel.

4·74 *Correlations with Temperature*

After lapse rate, temperature is the most obvious cause of similar variations in daily mean concentrations of smoke and sulphur dioxide. As might be expected, however, correlation with temperature is not evident in the summer months when artificial heating is unnecessary.

From September to March, inclusive, the correlation with temperature at 9 h. G.M.T. of daily mean smoke in central Leicester was $-0·45$, and of sulphur dioxide was $-0·51$. The effects of annual variation had been eliminated, although, since the annual variation of pollution is a result of the annual

variation of temperature, it would have been legitimate to retain annual variations. Correlation coefficients would be much increased by this procedure, but there would be the disadvantage that the variations considered would be partly periodic. There is a small but significant correlation of temperature with temperature gradient, and when groups of days with constant temperature gradient are considered by the method of partial correlations the above correlations are reduced to – 0·42 and – 0·50. Observations of 147 days were used. In winter, then, about 0·2 of the variance of smoke and sulphur dioxide is due to a common dependence on temperature, in which lower temperatures are associated with greater pollution. If any such evidence is needed, here is proof that we burn more fuel in cold than in warm winter weather.

From April to August, pollution was not significantly correlated with temperature. Observations of 115 days were used, and so any correlation exceeding 0·19 would be significant. Evidently we burn so little fuel for heating purposes in the summer months that there is no significant increase in pollution during cold periods in summer.

It was thought that in the spring and autumn months of March, April, September, and October, there might be specially high correlations with temperature, because many domestic fires would be lit on cold days which in warm weather would not be lit at all. However, no such increase in correlation was detected, and the annual variation of the correlation with temperature can be simply described as uniformly high in winter and negligible in summer.

4·75 *Correlations with Rainfall*

The correlations with rainfall of smoke and sulphur dioxide might be expected to differ from each other, because one constituent is soluble in water and the other insoluble. However, from 36 monthly means for Central Leicester, the correlations for both were very similar. Monthly mean sulphur dioxide, by the volumetric method, had a correlation with monthly rainfall of – 0·39, compared with the correlation for smoke of – 0·35. With *number of days* when a trace or more of rain fell, the correlations were – 0·44 for sulphur dioxide and – 0·48 for smoke.

These correlations are not entirely due to the direct effect of rain on pollution, because there is a significant correlation between number of rainy days per month and turbulence. When monthly mean lapse rate at Mildenhall is kept constant, the partial correlation of sulphur dioxide with number of rainy days is – 0·30, and of smoke is – 0·40. Only the latter is above the 5% level of significance, but the two figures strongly suggest that rain plays a part in cleaning the air of smoke and sulphur dioxide.

No meteorological variable has so far been found which strongly affects the concentration of one form of suspended pollution while leaving the other unchanged.

4·76 *Relation between Smoke and Visibility*

Observations of visibility were taken from station 9 daily at 9 h. G.M.T., and for this purpose a number of objects at known distances from the place of observation were selected. The objects at 2, 4, 7, and 10 km., i.e. $1\frac{1}{4}$, $2\frac{1}{2}$, $4\frac{1}{3}$, and $6\frac{1}{4}$ miles, were either in or through Leicester, and 90% of the recorded visibilities were in this range. Hence if visibility is reduced by smoke, there should be a negative correlation between daily visibility and daily mean smoke in Central Leicester.

To avoid the effect of annual variation, results were examined for three summer months, June, July, August, and for three winter months, December, January, and February. Visibility was expressed on a logarithmic scale. The correlation coefficient from 199 pairs of observations in summer was – 0·37, and from 148 pairs of observations in winter was – 0·46. Both these correlations

are significant, and they indicate that from one-fifth to one-sixth of the variance of visibility across Leicester was associated with variations in smoke concentration near ground level in Central Leicester.

Since changes in smokiness will clearly affect the visibility, while a change in visibility can hardly affect the smokiness (though both may be affected by some third factor), it is worth while to consider the regression of visibility on smoke. It was found from the original set of observations that when the smoke concentration was doubled the average distance at which objects could be distinguished decreased by a factor $0{\cdot}57 \pm 0{\cdot}07$. There was no significant difference in this factor between summer and winter. The factor is not significantly different from 0·5, and would therefore be in accordance with the statement that visibility is inversely proportional to smoke concentration.

If this is true, then, other things being equal, the distance to which the eye can see is the length of a unit column of air which contains a certain definite weight of smoke. The weight of smoke can be roughly calculated from information given in figures 4·21 and 4·41. For average meteorological conditions in summer, the *mass/area* concentration of smoke which is necessary to blot out vision is approximately 0·5 gram per square metre; in winter it is 0·8 gram per square metre. These estimates are liable to error because the measurements of the concentration of smoke were not in the direct line of the visibility observations.

The relatively low correlation between smoke and visibility would prevent single observations of visibility from being used for estimating the mean concentration of smoke in towns. But if every observation of visibility in a town were accompanied by a similar observation in the neighbouring country, a method of estimating smoke might be developed, though obviously it would break down in foggy weather.

4·8 Irregular Variation of Lead Peroxide Observations

There is evidence in Sections 3·41 and 4·21 of the practical value of lead peroxide observations, and this is amplified by many references in Chapter 5. It is therefore surprising and noteworthy that the *irregular* variation of sulphur determinations by the lead peroxide method does not give any useful information about the concentration of sulphur dioxide. Both turbulence and rainfall affect the reactivity of lead peroxide in the converse direction to their effect on concentration of sulphur dioxide. As a result, the yield of lead sulphate suffers relatively little irregular variation, and is not correlated with irregular variations in concentration of sulphur dioxide. This is not always a disadvantage; for instance, the lead peroxide method may be applied with all the more accuracy to determining the seasonal variation and the distribution of the *emission* of sulphur dioxide.

Monthly measurements of sulphur dioxide by the lead peroxide method have a much smaller variance than monthly means by the volumetric method. From 27 months' observations, the variance of lead peroxide results in central Leicester was $91(\%)^2$, after eliminating annual variation. The corresponding figure for monthly mean volumetric sulphur dioxide was $290(\%)^2$. From the square roots of these figures, the standard deviation of a lead peroxide estimate is 9·5% and of a volumetric estimate 17%.

4·81 *Turbulence and the Lead Peroxide Method*

The chief reason for the relatively low variance of lead peroxide estimates is probably that turbulence promotes the reaction between lead peroxide and the sulphur dioxide in the air; the more turbulent the air, the greater chance for each molecule of sulphur dioxide to collide with the lead peroxide surface. In the laboratory it was found that the rate of reaction between sulphur dioxide and lead peroxide was doubled when a fan was switched on.

On the other hand, it was shown in Section 4·521 that the more turbulent the air the fewer molecules of sulphur dioxide in a given volume of air. The reduction of concentration is therefore balanced by increased reactivity. As a check on this suggestion, the correlation between monthly mean temperature gradient at Mildenhall and monthly mean volumetric sulphur dioxide in central Leicester was +0·46; for lead peroxide results it was +0·09, which is not significant.

4·82 *Volumetric and Lead Peroxide Methods*

During 27 months, annual variations being excluded, the monthly lead peroxide results were not significantly correlated with monthly mean concentrations of sulphur dioxide. The estimated correlation was +0·23; since 26 months' observations were used, the coefficient would have to be outside the range ±0·39 to be regarded as significantly different from zero. This means that the irregular variations of lead peroxide results are due to other causes than irregular variation in concentration of sulphur dioxide, and further confirms the contention of the previous paragraph.

4·83 *Rainfall and the Lead Peroxide Method*

The lead peroxide method is insensitive to variations in sulphur dioxide concentration due to weather. This is shown by the above-mentioned lack of correlation with turbulence. It is also shown by the sign of the correlation with rain; for the correlation of lead peroxide results with monthly rainfall was +0·46, whereas the corresponding correlation of sulphur dioxide with monthly rainfall was – 0·39.

4·84 *Temperature and the Lead Peroxide Method*

The one meteorological variable which affects lead peroxide results similarly to volumetric results is temperature. The correlation of 27 monthly lead peroxide results with monthly mean temperature is – 0·43, and this is significant because less than 3% of random groups of 27 uncorrelated pairs of data are found to yield a correlation coefficient numerically greater than 0·43. For comparison, the partial correlation of monthly mean sulphur dioxide concentration with monthly mean temperature was – 0·39 (also significant), for 35 months, mean lapse rate at Mildenhall being kept constant. It is important that these correlations are nearly equal, for it follows that the reactivity of lead peroxide with sulphur dioxide does not depend strongly on temperature. If it had done so, the lead peroxide method would have led to false conclusions about the yearly cycle of atmospheric sulphur dioxide. Wilsdon and McConnell[15] showed from theoretical considerations that temperature should have a small effect, in which a rise of 1° C. increased the reactivity by about 0·4%. This would be too small to be detected in the Leicester Survey results.

4·85 *Reactivity*

The ratio, *rate of sulphation of lead peroxide* to *concentration of sulphur dioxide*, is a direct measure of reactivity. Reactivity is strongly correlated with both rainfall and the number of rainy days per month, the coefficients being +0·64 and +0·76 respectively, from 26 months' observations. In months with 1 inch of rain or with four rainy days more than normal, the reactivity was on an average 9% more than normal. The reason was shown in the laboratory to be because lead peroxide is more reactive when its surface is wet; the present type of cowl over the lead peroxide candles does not prevent them from becoming wet in rainy weather.

The correlation of monthly mean reactivity with temperature gradient at Mildenhall was – 0·46, confirming that reactivity increases with increasing turbulence.

Reactivity is not significantly correlated with temperature, and has no significant annual variation, such as might be caused by a temperature effect.

There were not sufficient data to show that reactivity is significantly correlated with monthly mean wind velocity, although, since both variables are correlated with turbulence, they must be correlated with one another. Wilsdon and McConnell (loc. cit.) found that reactivity was approximately proportional to $u^{\frac{1}{4}}$. It can be shown that such a slight dependence would not normally lead to a significant correlation in 26 months' data.

4·86 *Summary*

Statistical investigation of the reactivity of lead peroxide with sulphur dioxide confirms the inferences of Sections 4·81, 4·82 and 4·83. The lead peroxide method should therefore not be used to measure irregular, short-term variations of atmospheric sulphur dioxide; but it is particularly suitable for measuring the distribution of sulphur dioxide. The method would be made more accurate for measuring the yearly cycle by protecting the candles more adequately against rain, for it would be better if rainfall, like turbulence, were uncorrelated with the yield of lead sulphate; i.e. if the increased rate of reaction in wet weather were no more than sufficient to balance the decrease in concentration of sulphur dioxide. In summer the ground dries quickly after a shower, but in winter it may continue wet for hours. The same is probably true of lead peroxide candles, and so the average reactivity is probably higher at present in winter than in summer. This would account for the greater range of annual variation by the lead peroxide method than by the volumetric method.

5·0 PRACTICAL ASPECTS

5·1 Introduction

In the Leicester Survey there was no control over many of the variables likely to affect pollution. As far as is known at present these are: rate of emission, which varies with time and place; place of emission in relation to place of observation; wind direction and speed, turbulence, temperature, rainfall and previous history of the cloud from which rain is falling; the shape, retentivity, and power of adsorption of obstructions on the earth's surface; the rate of reaction of one form of pollution with another and with plants, animals, soil, and building materials. Of these variables the only ones which could be controlled were time and place of observation.

In consequence, it has often been necessary in Chapters 3 and 4 of this report to refer, in lengthy digressions, to variables other than those under immediate consideration. The questions considered have been of the type "Why do observations of pollution vary in such-and-such a way?" If it had been possible to consider "How does a variation in so-and-so affect pollution?" the conclusions would have arranged themselves in a more orderly manner. It now remains to collect the conclusions of Chapters 2, 3 and 4 in a convenient form. This is done in the present chapter by considering strictly practical questions.

A vitally important question at the present time is that of smoke abatement and control. In a discussion of this subject the distribution of smoke in cities is considered in relation to the diffusion of smoke from cities. The dilution of smoke is considered with special reference to the problem of deciding what is the least objectionable time at which to emit unavoidable pollution. Natural air-cleaning processes are enumerated, with an estimate of the speed with which they operate. Finally, the effect of town acreage and population on smoke concentration is considered, because it is one of the matters which authorities should face when they are planning new towns or new satellites of existing towns. Smokeless zones are compared, somewhat to their disadvantage, with other types of reform.

The control of sulphur dioxide is bound up with smoke abatement, but the methods of voluntary control are more difficult; and natural processes which limit the concentration of sulphur dioxide in towns are not the same in all respects as those which limit smoke.

Until atmospheric pollution is reduced to its lowest possible amount, it will be important to keep records of its intensity. The instruments for measuring different aspects of pollution are enumerated, and new suggestions are made for the deposit gauge, smoke filter, automatic filter, lead peroxide apparatus, and apparatus for measuring daylight. The importance of choosing suitable sites is considered briefly; also the use of instruments for obtaining such information as the distribution of pollution in towns and its variations with time. Attention is drawn to the special uses of the smoke-sulphur ratio.

Among particular problems, smoke forecasting is considered as a practical possibility, together with its public and domestic applications. Methods of identifying pollution and tracing it to its source are discussed briefly. The chapter ends with a consideration of future research, as distinct from routine measurements of pollution. Some of the suggested items of research are of general interest, while others are directed to the difficult question of air exchange in the lower atmosphere, and how it affects pollution.

5·2 Smoke Abatement and Control

It is deduced in Section 4·311 that more than half the coal used in winter in Central Leicester is used for domestic purposes, but this estimate may be too high if more coal is burned domestically on Sundays than weekdays. A check on this may be made from records of coal consumption in Leicester and the country as a whole. In Great Britain in 1938, about 63 million tons of coal were used, directly and indirectly, for domestic purposes[28]; that is, about 1·4 tons per head of population. Central Leicester has about 100,000 inhabitants, and if they burn coal at the average rate they must use about 140,000 tons per year. In the winter six months they would use about 100,000 tons. According to information supplied by the Ministry of Fuel and Power, the (wartime) industrial consumption of coal in Leicester is probably about 75,000 tons in the six winter months. The inference from Table 4·311 therefore appears to have been reasonably accurate.

From the same table it is estimated that about three-quarters of the smoke emitted in winter in Central Leicester is emitted from domestic chimneys. It follows that nearly twice as much smoke is produced per ton of coal burned domestically as industrially, and this is including as domestic the coal burned to make electricity for domestic consumption.

By a different line of argument in Section 3·53, it is concluded that the population of the outer suburbs, whether at work or at leisure, makes about as much smoke in proportion to the coal burned as the population near the centre. It therefore seems likely that in Great Britain generally an average of about twice as much smoke per ton of coal is made domestically as industrially. This is an average figure, since the method of burning coal varies very much according to the different industrial and domestic appliances used. The annual consumption of coal for all purposes in Great Britain was about 177 million tons in 1938.[28] Of this, the 63 million tons which were used domestically must have produced nearly as much smoke as the remaining 114 million tons which were used for all other purposes. Thus, in Great Britain as a whole, about half the smoke is of domestic origin.

Much has been done, by means of by-laws and by smoke inspectors of local authorities, to limit the emission of smoke from industrial chimneys. The next step is to reduce, and ultimately prevent, the emission of smoke from domestic chimneys. Comments on this social and economic problem are beyond the scope of this report, but reference may be made to "Atmospheric Pollution and Domestic Heating".[29] On the other hand, there is evidence in this report of what is the maximum smoke to expect in a town where the mean concentration of smoke is known; of how much of the smoke from one city may reach others; and of how natural processes assist in preventing concentrations of smoke from being much higher than they are.

5·21 *Smoke Concentration in Cities*

The smokiest district in Leicester, in all wind directions and velocities, was the centre (Section 3·48). In other towns it can be assumed, therefore, that most smoke will be found where most is emitted. The maximum effect of wind is to displace the point of maximum concentration by $\frac{1}{2}$ mile (Section 3·491).

In summer the mean smoke concentration at the centre of Leicester was 170 micrograms per cubic metre. The highest daily mean was 3·7 times as much. The highest hourly mean was 7·1 times as much. In winter the corresponding concentrations were 410 for the mean, 4·4 times as much for the highest daily mean, and 5·4 times as much for the highest hourly mean. It is useful to know what is the highest concentration to expect in any particular neighbourhood, and the above figures suggest that about 6 times the winter mean can be

expected. Observations at Stoke-on-Trent and Victoria Street, Westminster, are consistent with a factor of about 6·5.

5·211 *Dependence of smoke on population.* Since a large part of the country's smoke is emitted from domestic chimneys, it is likely that the concentration of smoke in any town depends in a definite way on its population. In addition to Leicester, there were eight other towns in the British Isles where measurements of smoke concentration were made in 1937-9. The smallest of these towns was Coventry, with a population of 200,000, but it is of special interest to know the probable smoke concentration in much smaller towns. This can be estimated from the observations in certain Leicester suburbs in selected wind directions. For example, by considering the distribution of population in Leicester, it can be estimated that the smoke at station 3 (Westcotes), in westerly winds, would be about equal to the smoke at the centre of a town of 60,000 inhabitants. In a similar way to this, other suburbs can be found which are equivalent in certain winds to towns of different sizes. The resulting information about the effect of population on smoke concentration is given in Table 5·211, which also contains results from the eight other selected towns in the British Isles where observations have been taken.

TABLE 5·211 *Dependence of Smoke on Population*

Town	Wind Directions	Population	Winter Mean Smoke mg./cu.m.	$\frac{\text{Smoke} \times 10^4}{\sqrt{\text{Population}}}$
Leicester:				
Station 10	NE, E, SE	10,000	0·07	7
Stations 4 and 5	SW, W, NW	30,000	0·15	9
Station 3	S, SW, W, NW	60,000	0·19	8
Station 2	SE, S, SW, W	100,000	0·18	6
Station 14	N, NE, E, SE, S	140,000	0·23	6
Coventry	all	200,000	0·30	7
Cardiff	all	220,000	0·08	2
Leicester (Stn. 1)	all	260,000	0·33	6
Stoke-on-Trent	all	270,000	0·59	11
Kingston-upon-Hull	all	320,000	0·34	6
Dublin	all	320,000	0·42	7
Edinburgh	all	440,000	0·51	8
Glasgow	all	1,090,000	0·66	6
London	all	8,200,000	0·84	3
				mean 7

Note: Observations at the Leicester stations were with the simple smoke filter, and were corrected for country smoke. Observations in all other towns were with the automatic filter, and were not corrected for country smoke.

Table 5·211 clearly shows that, in general, the smoke of a town increases with its population. With three exceptions the observations conform with the formula:

$$\underset{\text{(mg./cu.m.)}}{\text{Winter mean smoke}} \times 10^4 = \sqrt{\text{Population}} \times (7 \pm 1)$$

Thus emerges the empirical rule that the smoke concentration in a town is proportional to the square root of its population. The exceptions to this rule are Cardiff, Stoke and London. In London the mean smoke concentration is more than in any of the other towns, but it is not in proportion to the population. This is apparently because coal is burned less smokily than elsewhere. At Stoke, the concentration of smoke is much higher than at other towns of

the same size. It seems likely that the industries of Stoke produce more smoke than those of the other towns. Cardiff, with only about a quarter as much smoke as other towns of the same size, has the reputation of being an exceptionally clean city. The commonly accepted reason for this is the practice of burning low-volatile coal in domestic grates instead of bituminous coal. This is a powerful argument in favour of smokeless fuels.

The numbers in the last column of Table 5·211 are obtained by dividing the smoke concentration by the square root of the population. It can be seen that these numbers will serve as figures of merit, being low when coal is burned smokelessly. Another figure of merit is the smoke-sulphur ratio, discussed in Section 5·522.

Table 5·211 will serve to indicate the probable mean smoke concentration at the centres of other British towns. To estimate the concentration in non-central districts, a knowledge of the relative distribution of smoke is required, and the only town for which this knowledge is available is Leicester. For other towns, however, Figs. 3·41 or 3·48 can serve as a rough guide to the distribution of smoke which might be expected.

5·22 *Diffusion of Smoke from Cities*

Observations in Leicester support the view that within a large, uniformly populated area, but not too near its windward edge, the concentration of smoke in surface air will vary very little from place to place. There is no accumulation of smoke in surface air as it blows across a town. Instead, the upper surface of the smoke pall apparently rises to greater and greater heights above the surface (Section 3·491).

In country districts four miles from Leicester there is considerably more smoke when the wind is blowing from Leicester than when it is coming from other directions (Section 3·493). The effect is most marked in fresh winds of more than 10 m.p.h. There is then about 8 times as much smoke downwind as in other directions. In average winds of 7 m.p.h. there is from 2 (in summer) to 3 (in winter) times as much smoke downwind. These figures refer to smoke produced in Leicester, and a correction has been made for pollution from other industrial districts to the windward of Leicester.

The amount of excess smoke found 4 miles downwind varies from 10 to 34 per cent. of the smoke in Central Leicester. This is about the same as the average local smoke 2 to 3 miles from Leicester.

Information about the diffusion of smoke over distances as great as 35 to 90 miles can be derived from Section 3·47. The dependence of country smoke on wind direction is very striking in Fig. 3·47, and, in particular, the high concentrations in N, NW, W and SW, and SE winds are strongly suggestive that the smoke originates in Yorkshire (West Riding) and Derbyshire, Lancashire and Staffordshire, Birmingham district, and London respectively (see for instance Fig. 3·1(b)).

Let it be assumed that the excesses of these concentrations over the concentration in east or north-east winds are due to smoke from the above-mentioned populous districts; let it also be assumed, as a working hypothesis, that the smoke produced by a district is proportional to its population. The winter concentration of smoke between 35 and 90 miles downwind from a polluted area can then be approximately represented by the formula:

$$S = \frac{25000\,N}{x^2}$$

where S is the smoke concentration in micrograms per cu. metre,
N is the population in millions of the source of smoke,
and x is the distance in miles from the source.

TABLE 5·22 *Diffusion of Smoke to Leicestershire from other Districts:*

$$S = \frac{25000\,N}{x^2}$$

	x Distance (miles)	N Population (millions)	S Smoke Concentration near Leicester in Winter micrograms/cu. metre	
			calculated	found
Birmingham District . .	35	2·0	41	35
W. Riding and Derby . .	50	4·8	48	51
Lancs. and Staffs.	70	6·5	33	32
London	90	8·2	25	19
Leicester	4	0·25	390	71

Table 5·22 shows that the formula agrees moderately well with observation, except that the calculated value of London smoke received in Leicester is appreciably more than the observed value. This may be because there is more modern fuel-burning equipment in London houses (see Section 5·32); it would then be untrue to extend to London the assumption that the smoke produced by a district is proportional to its population.

It is interesting to note that the formula is an inverse square law of distance. This is to be expected if the areas in question can be regarded as point sources[25]; yet the Birmingham district, for instance, subtends nearly 90° at Leicester. An inverse square law can only hold, even for point sources, if pollution can spread steadily upwards as well as sideways. There is a definite limit to upward spreading when the smoke reaches the stratosphere, at a height of about 7 miles. Evidently after travelling 90 miles horizontally, the amount of smoke which has travelled 7 miles upwards is negligible. At some distance not much greater than 100 miles, however, it is to be expected that the ceiling-effect will come into force, and beyond this distance the concentration of smoke will be inversely as the distance.

An attempt to include the pollution 4 miles downwind from Leicester in the formula of Table 5·22 was unsuccessful. At this proximity to a large town such air as is introduced by diffusion sideways will have passed through the suburbs at least, and diffusion upwards is the only factor which can diminish concentrations appreciably. Hence the concentration of smoke will diminish as the distance, rather than the square of the distance. This has also been deduced from consideration of a continuous line source[25]. If there were an inverse linear law of distance up to 10 miles from the source, and an inverse square law beyond 10 miles, the agreement would be satisfactory, but in practice there will undoubtedly be a transition zone.

Summing up, the concentration of smoke is independent of position at points within a large uniformly populated area; between, say, 4 miles and 10 miles downwind from a town the size of Leicester, smoke diminishes as the distance (diffusion upwards only); between 10 miles and about 100 miles downwind of towns and regions which may be treated as point sources, smoke diminishes as the square of the distance (diffusion sideways and upwards); beyond about 100 miles smoke probably diminishes more slowly again, ultimately as the distance (diffusion sideways only). The distances in this statement are only approximate; also deposition of smoke has been entirely neglected. It seems likely that Leicester and similar towns may be treated as point sources of smoke at all distances beyond about 10 miles.

5·23 *Dilution of Smoke*

In normal weather, the air over Britain undergoes a thorough mixing process, which is conducted partly by wind and partly by thermal turbulence. Mixing begins to operate from the moment smoke leaves the chimney, and in ordinary weather smoke is diluted by clean air very quickly indeed. For example, the concentration of smoke at the chimney top may be 10,000 milligrams per cubic metre. Twenty feet downwind, say 2 seconds later, the smoke may cease to be sufficient to screen from view objects behind it. Its concentration would then be about 200 milligrams per cubic metre. A hundred feet downwind the smoke may be entirely invisible, and have a concentration of about 5 milligrams per cubic metre. Four miles downwind, i.e. in about half an hour, its concentration would probably be about $\frac{1}{10000}$ milligram per cubic metre, if the diluting air were perfectly clean.

The main result of mixing is to save the maker of smoke from much of the unpleasantness he might have caused. On the rare occasions when mixing breaks down completely, smoke-emitting districts are in unhappy plight; how much more unpleasant are town fogs than country fogs! The effect of breakdowns in mixing can be seen in Section 4·71. There were six days during three winters when the daily mean concentration of smoke in Central Leicester exceeded $3\frac{1}{2}$ times the normal value, and one day when it was 5 times the normal value. In Section 4·711 it is shown that rate of mixing is more strongly dependent on temperature gradient than wind velocity.

5·231 *When to emit unavoidable pollution.* Turbulence is usually greatest when the sun is high, and in clear windy weather typified by cumulus clouds. If smoke and odours must be made at all, the times to make them are when turbulence is greatest. These are the best times for conducting operations which produce any kind of suspended impurity near the ground. Even to-day, operations such as soot blowing, and cleaning filters at sewage works, are frequently done after dark, i.e. at about the worst time.

Such operations as handling coal, which produce grit and dust, are altogether different. These should be conducted as often as possible in calm weather so that the grit is deposited near where it is made.

5·24 *Natural Air-cleaning Processes*

Mixing is not strictly a cleaning process, because it does not remove smoke from the air. In time, if nothing else happened, the air of the whole world would become contaminated and ultimately life would be impossible. Before this catastrophe could occur, however, smoke would settle out under gravity rapidly enough to maintain equilibrium with the emission of smoke. (In high concentrations, smoke particles coagulate and cling together in chains sometimes several centimetres long, and much smaller chains, about $\frac{1}{10000}$ cm. long, occur in atmospheric smoke.) In the atmosphere, however, deposition by turbulence is probably far more important than by settling. Even the lightest smoke particle is so much heavier than a molecule that it may be deposited centrifugally when a fast-moving air current takes a sudden curve near an obstacle. If polluted air is drawn through a fine jet into a larger glass tube a deposit of smoke appears in the jet and also inside the larger tube. This only happens when the jet is narrow enough, and the flow fast enough to produce turbulence. The same considerations explain why air filters can catch particles much smaller than their pore size. It is reasonable to expect vegetation and all irregularities of land surface to act, though less efficiently, in a similar way.

In Section 4·75 it is shown that the concentration of smoke is less on rainy days than on dry days. After allowing for secondary effects, it seems probable that an appreciable quantity of smoke is removed from the air by rain as it

falls. More smoke may also be removed, to be deposited later, by rain clouds, for there is continuous movement within them of water and ice particles. It has also been suggested that fog droplets, sinking slowly to the ground, take smoke particles with them. Evidently the ways are many in which the air can rid itself of impurities. Water droplets are extremely useful to this end, though not indispensable.

5·241 *Half-life of suspended smoke particles.* How long, on an average, does a particle of smoke remain suspended iu the air? The answer to this question is important, because it helps to find how big an area round a town may be affected by its smoke.

Over long periods, sufficiently long for weather variations to be smoothed out, it can be assumed that smoke is deposited at a rate proportional to its mean area concentration. This means that if the emission of smoke were suddenly stopped the concentration of smoke would diminish according to an exponential law. If τ is the average life of a smoke particle in the suspended state, then it can be shown that

$$\tau = \frac{A}{-dA/dt}$$

where A is the mean total weight of smoke in a square metre column of air, and $-dA/dt$ is the mean rate at which smoke is deposited on each square metre of ground. Since only a fraction of the smoke is deposited near where it is emitted, it is better, when evaluating τ, to consider a very large area.

The first step is to make an estimate of A, the mean area concentration of smoke. The winter mean smoke concentration in surface air in the Midlands is likely to be between 0·7 mg./cu.m. (observed in Stoke) and 0·08 mg./cu.m. (observed outside Leicester), and is probably nearer the latter figure—say 0·15 mg./cu.m. The height to which smoke extends has not been observed systematically, but observations in Germany[30] suggest that the total smoke may be estimated by assuming a uniform concentration up to heights ranging according to turbulence from 200 metres to 1000 metres, with clean air above. If the mean height is 700 metres, the value of A for the Midlands is about 0·1 g./sq.m.

The second step is to evaluate $-dA/dt$, the mean rate of deposition of smoke. The most rural of the Leicester deposit gauges, at station 7, received an average of 0·3 g./sq.m./month of insoluble combustible matter. At Loggerheads, Staffs., the average was 0·2 g./sq.m./month, even lower, while the highest average in the Midlands was about 3·0 g./sq.m./month. Therefore $-dA/dt$ for the Midlands is probably about 0·5 g./sq.m./month.

It follows that $\tau = 0{\cdot}1/0{\cdot}5$ month $= 0{\cdot}2$ month $= 6$ days. This result is liable to errors, (a) because of insufficiency of deposit and smoke determinations in the Midlands, (b) because the Midlands may not be a sufficiently large area for the method, (c) because the insoluble combustible matter in deposit gauges may not all have been smoke, and (d) because smoke may be more readily deposited on vegetation and surface irregularities than in the deposit gauge. Six days is probably the best estimate, from the information at present available, of the average time for which a smoke particle remains suspended in the air.

In six days, the air at heights below 700 metres may travel any distance up to 6000 miles, but 500 to 2000 miles would be the usual distance. Thus the smoke from our densely populated industrial areas spreads all over England. In suitable winds we might receive smoke from the Rhineland, but we are not likely to receive much smoke from America, unless the rate of deposition on sea is much less than on land.

At present, smoke abatement is a problem for local authorities. If there

is a stage when some cities have achieved smokeless air before their neighbours, the problem may become a national one. In certain circumstances, for instance on the continent of Europe, it may even become an international problem.

5·25 *Smokeless Zones*

The problem of reducing smoke in large cities below a stipulated value can best be solved by drastic reforms in methods of burning raw coal, particularly in the home. The only, but impracticable, alternative appears to be to break the city up into towns of about 50,000 inhabitants, with several miles of open country round each town (see Table 5·211).

It has been suggested that a step in the direction of reform would be to prohibit the emission of smoke in a central area of the city—for instance, in the principal centre of shopping and entertainments—or near municipal buildings, cathedrals and other objects of architectural interest. It is undoubtedly a step in the right direction to abolish smoke anywhere, and the citizens of a town might be glad to co-operate in a scheme of this sort, but they must not look forward to spectacular results. If the ordinary citizen were to visit the central park of his town, on a hazy day in winter, he would not be able without instruments to detect any difference in smokiness from the rest of the town. Now a central park *is* a smokeless zone, probably more nearly smokeless than a commercial district could be, and the inference is clear. A smokeless zone suffers considerably from the smoke emitted in a large area round it, and, although the surroundings all benefit from their proximity to a smokeless zone, the advantage is divided among so many districts that the share of each is small.

Section 3·71 describes some measurements of smoke concentration in Hyde Park and Kensington Gardens, London. They show that the average reduction in smoke to be expected at the centre of a square mile free from smoke emission is 25 to 30%, and that the actual reduction may vary from about 15% on non-turbulent days to 75% on very turbulent days. These results are for very fine smoke particles, and they are probably also true for sulphur dioxide. The improvement in pollution consisting of particles so large that they quickly fall out of the air is greater than that for smoke, given above (Appendix 6·3). It is recommended that any experiments with smokeless zones should include systematic observations of pollution, so that the citizen may learn that he really does improve the air if he prevents pollution.

5·3 Sulphur Control

The differences between smoke and sulphur dioxide, as forms of pollution, are not so much bound up with the differences between a solid and a gas as with the fact that one is an avoidable and the other an unavoidable product of combustion. When raw coal is burned there is no need for smoke to be formed, but since all coal contains from 1 to 4 per cent. by weight of sulphur, it is inevitable that sulphur dioxide is produced.

Nevertheless, there is one way of preventing at least some sulphur dioxide from being formed, for up to half the sulphur may be removed from coal by washing. Washing is in many cases worth while, merely to save the expense of transporting waste dirt and mineral matter from colliery to consumer.

The other ways of controlling sulphur dioxide are by chemically transforming the coal before burning it and by direct removal of sulphur dioxide from flue gases. The latter process is already in use in certain large power stations, and could be extended, at a cost, to smaller undertakings. When coal is transformed into gas, coke and by-products, most of the sulphur is removed from the gas, but not from the coke. It is therefore an advantage to use more gas, and more electricity from certain power stations. The increasing use of these fuels,

especially where they have replaced coal for domestic cooking purposes, must have already begun to reduce the national output of sulphur pollution.

Sulphur control is a domestic as well as an industrial problem, but the industrial part of the problem seems more hopeful of solution than the domestic part. On the whole, sulphur control is less urgent than smoke abatement, although on rare occasions, when the concentration of sulphur dioxide is high enough, it may cause loss of life, after oxidation to sulphuric acid.[29]

5·31 *Sulphur Dioxide Concentration in Cities*

In all wind directions and velocities, the maximum concentration of sulphur dioxide in Leicester was at the centre (Section 3·48). Sulphur dioxide has a greater tendency than smoke to be concentrated near the centre of Leicester, because its chief sources are nearer the centre (Section 3·51). As with smoke, it can be assumed that most sulphur dioxide will be found where most is emitted.

In summer the mean concentration of sulphur dioxide at the centre of Leicester was 0·06 volume per million. The highest daily mean was 2·9 times as great. The highest hourly mean at Station 1(b) was 5·5 times as great as the mean at Station 1(b). In the same way in winter, the mean concentration was 0·14 volume per million; the highest daily mean was 3·0 times as great; the highest hourly mean was 6·4 times as great.

In the absence of volumetric determinations, the mean concentration of sulphur dioxide may be estimated from results by the lead peroxide method. The mean rate of sulphation is expressed in milligrams per day per 100 cm.^{2} of lead peroxide. This figure should be multiplied by 0·025 to give a rough estimate of the mean concentration of sulphur dioxide, in volumes per million. There is, however, a considerable variation in the factor from one site to another (between 0·01 and 0·04), not only in Leicester but in the country as a whole. Until the reason for this variation is more fully understood, the factor 0·025 should be used with caution.

5·32 *Diffusion of Sulphur Dioxide from Cities*

At distances of about 4 miles from Leicester, there is a well marked increase in concentration of sulphur dioxide when the wind changes to such a direction that it blows from Leicester. The increase, expressed as a ratio, is greater than the corresponding increase in smoke, but numerical values are probably too large because the effect of ammonia on volumetric determinations of sulphur dioxide is greatest in country districts.

The problem of diffusion over larger distances may be treated analogously to that for smoke, using the data of Section 3·47. An inverse square law of distance again gives satisfactory agreement, for distances from 35 to 90 miles. The winter concentration of sulphur dioxide can be approximately represented by the formula:

$$T = \frac{320\,N}{x^2}$$

where T is the SO_2 concentration in volumes per 100 million,
N is the population, in millions, of the source of SO_2,
x is the distance in miles from the source.

The concentration T is the extra sulphur dioxide attributable to the distant source. It is not liable to errors due to ammonia unless appreciable quantities of ammonia are emitted by towns, and this seems unlikely in view of Fig. 3·43.

TABLE 5·32 *Diffusion of Sulphur Dioxide to Leicestershire from other Districts: $T = 320N$*

	x Distance (miles)	N Population (millions)	T SO_2 concentration near Leicester in Winter (vols per 100 million)	
			calculated	found
Birmingham District	35	2·0	0·52	0·55
W. Riding and Derby	50	4·8	0·61	0·51
Lancs. and Staffs.	70	6·5	0·42	0·47
London	90	8·2	0·32	0·31
Leicester	4	0·25	5·0	1·5

Table 5·32 compares the values of T calculated by formula with the observed values. Agreement is fairly good for distances from 35 to 90 miles, but, as with smoke, the calculated value at a distance of 4 miles is much too high. From London as much sulphur dioxide is found as the formula predicts, whereas in Table 5·22 less smoke was found than had been expected. This may be because the domestic heating equipment in London is more efficient than in the provinces, or it may be due to greater fuel economy, combined with a higher percentage of sulphur in London's coal. The former explanation is rather more plausible, and if true it constitutes a practical argument in favour of efficient domestic heating equipment.

5·33 *Natural Removal of Sulphur Dioxide*

The dilution of sulphur dioxide by mixing with cleaner air probably occurs at the same rate as the dilution of smoke, for molecular diffusion is unimportant in the free air, and eddy diffusion is equally effective with both types of pollution.

Deposition by falling rain, also, according to Section 4·74, is of about equal importance in removing smoke and sulphur dioxide. Although it may react with ammonia and water vapour to form solid ammonium salts, sulphur dioxide is unlikely to become physically or chemically attached to large particles other than water; dry deposition by gravity is therefore negligible. It is difficult to say whether sulphur dioxide is more liable than smoke to be deposited by small eddies; dry ground will retain extremely few of the sulphur dioxide molecules which collide with it, although wet ground may retain a somewhat greater fraction.

These considerations suggest that the rate of removal of sulphur dioxide from the atmosphere is of the same order as that of smoke, and calculations by a method strictly parallel to that of Section 5·231 confirm this suggestion. The winter mean concentration of sulphur dioxide in the Midlands appears, from the limited observations available, to be about half the winter mean concentration of smoke (0·08 mg. per cubic metre, equivalent to 0·03 volume per million). The winter mean rate of deposition of sulphur dioxide is about equal to the rate for smoke (0·5 gm. per square metre per month). It follows that the average life of a sulphur dioxide molecule is about half that of a smoke particle (i.e. about 3 days).

According to "Heating and Ventilation"[28] about three times as much sulphur dioxide as smoke is emitted into the air of Great Britain each year. In winter the rate of emission of sulphur dioxide will be possibly twice that of smoke. Now the average concentration of sulphur dioxide in winter is only about half

that of smoke. Hence from this line of argument one would expect the average life in the atmosphere of a sulphur dioxide molecule is about one quarter of the average life of a smoke particle. Perhaps the agreement between this conclusion and that of the previous paragraph is as good as could be expected.

5·4 Instruments and Methods of Measuring Atmospheric Pollution

Four standard instruments are in use for the investigation of atmospheric pollution in Great Britain. These are the Deposit Gauge, the Automatic Filter, and two methods of determining sulphur dioxide. These four types were in use at Leicester, and also four others which were under test. The four additional types were (a) the Smoke Filter, (b) an hourly volumetric sulphur dioxide apparatus, (c) a directional lead peroxide gauge, and (d) an ultra-violet daylight integrator. Most of these eight instruments are very simple, but simplicity can sometimes be bought only by sacrificing accuracy. There are also difficulties of interpretation, since one instrument is often assumed to give results representing a whole district. This is why great instrumental accuracy is not needed, and why it is sometimes better to use many simple instruments than a few elaborate ones. After the intensive observations at Leicester, however, several suggestions which may save labour or reduce errors have arisen. The methods of using the instruments may also be modified to suit special requirements.

5·41 *Deposit Gauge*

In Section 2·213 attention was drawn to the great uncertainty as to where deposited material originates. There is evidence in Sections 4·62 and 4·64 that soluble matter originates at a greater distance than insoluble, because the soluble matter in two gauges $1\frac{3}{4}$ miles apart is significantly correlated, while the insoluble matter is not. It seems likely that much of the insoluble matter in gauges usually originates from industrial chimneys within $\frac{1}{2}$ mile. Now the industries of a town are usually much less evenly distributed than, say, dwelling houses; therefore a single deposit gauge, receiving material from within a radius of about $\frac{1}{2}$ mile, cannot yield results which are representative of a whole industrial town. This is especially true if the gauge is located in a park or large open space (Section 6·2). Furthermore, a change of wind direction brings different industrial chimneys into range of a deposit gauge; this is clear from the correlations of deposits with wind direction in Table 4·61.

The demerit of monthly deposit gauge results, then, is that they are not representative of a definite region. In the Investigation of Atmospheric Pollution this difficulty is partly overcome by averaging deposits over a long time, and thereby smoothing out wind-directional effects. In two successive periods of 5 years, for instance, it is reasonably sure that the area represented by a given deposit gauge is the same. But this method does not permit the deposits of different districts or different towns to be compared, unless many deposit gauges are used.

A better resolution of the difficulty would be to use batteries of smaller deposit gauges. For example, 25 gauges with 4″ collecting funnels, placed $\frac{1}{2}$ mile apart, would sample an area of about 4 square miles. The monthly yield of deposit would be about 3 times that of a single 12″ gauge. There would normally be no reason to analyse the deposit of individual gauges separately, and the labour of analysis would not much exceed that for a single standard gauge. The labour of collecting deposits at the end of each month would be greater, but would be thoroughly justified by the increased dependability of the results. A single month's results would then show, with considerable accuracy, what deposit had fallen on 4 square miles of an industrial district.

The effect of, say, a big new industrial plant could be determined in a year instead of 5 years, and, if need be, useful preliminary observations could be made of the district while the plant was being erected. If desirable, comparisons of one industrial district with another could be made, by using two batteries of deposit gauges.

Research is still needed to determine the optimum distance between individual gauges of a battery.

5·42 *Smoke Filter*

Many local authorities still have no standard equipment for observing smoke concentration, although it is recognized that the smoke nuisance can and should be reduced in the interest of the citizen. For purposes of detecting upward and downward trends in smoke concentration, the daily reading smoke filter offers advantages over the automatic filter; in the Leicester Survey it was most useful for observing the variations of smoke with time and position.

In Section 2·323 it was shown that the standard error of a single day's observation with the smoke filter was 10% to 5%, for a suitable density of stain. The reason for this large error is not clear, but it may be connected with the extremely irregular path of light through the filter paper during the photometric readings. Possibly a method of measuring the reflection coefficient rather than the absorption coefficient of the smoke stain would be better.

Where a daily standard error of 20% is not a serious drawback, the direct visual method of estimating reflection coefficients should be used. For this, the only necessary equipment is the Owens' scale of shades, which is normally supplied for use with the automatic filter. When a month's readings are to be averaged, daily casual errors of 20% are not important, because the monthly means will then have standard errors of only about 4%. As a routine instrument, contributing to a local authority's standard observations of atmospheric pollution, the smoke filter is recommended to be used with the Owens' scale of shades. The same type of filter paper should be used as for the automatic filter.

5·421 *Automatic filter*. In its present form the automatic filter is most suitable for use in very smoky areas. In cleaner districts a high proportion of the readings are less than 1 on the scale of shades, with the result that daily and monthly averages are less reliable than they might be. This difficulty may be easily overcome by the addition of a supplementary reservoir, enabling, say, 10 litres of air to be sampled at a time, instead of 2 litres. Experience has shown that, in spite of the greater volumes of water and air, hourly readings can be obtained with such an arrangement.

The automatic filter measures primarily the daily cycle of smoke concentration. It may also be used to determine the yearly and weekly cycles, trends and irregular variations, but it is unnecessarily elaborate for these purposes, when compared with the daily reading smoke filter.

5·422 *Monthly reading smoke filter*. To estimate the mean distribution of smoke in and around a town, 12 or more smoke-measuring instruments are needed at widely scattered points. The time required for visiting these points might prohibit the use of daily reading instruments for such a survey. It is therefore of interest to consider whether a monthly reading instrument could be devised, especially for use in surveys.

The amount of air required to make a smoke stain of suitable intensity and size (1 or 2 inches diameter) varies from 10 to 500 cubic feet. Electrically driven pumps are available which can draw 50 cubic feet of air per day through a 1-inch circle of filter paper, and one such pump was in use for nine months before it needed any attention. By placing a second filter of suitable resistance in the clean air stream between the standard filter and the pump, the volume sampled could be reduced satisfactorily to the desired quantity. With such an arrange-

ment, the rate of pumping would be nearly uniform throughout the month, being but slightly reduced by clogging of the standard filter. Hence there should be little difficulty in designing a monthly reading smoke filter.

It would be important to estimate the mass of smoke on each stain as accurately as possible, and the standard error of 20% by the visual method would be rather unsatisfactory. A photoelectric method of measuring the reflexion coefficient of a stain would give photometric readings accurate to about 2%, and after conversion it is probable that the weight of smoke would be liable to a standard error of 5% to 10%.

Another method suitable for more accurate monthly determinations of mean smoke concentration is the weighable smoke filter referred to in Section 2·33. The smoke is trapped by asbestos fibres, packed in aluminium tubes, and because of their non-hygroscopic nature these filters can be weighed accurately. It is an advantage to have as great a weight of smoke as possible, and 10,000 cubic feet of air per month would be a suitable rate of sampling. The weight of smoke in each sample would then be 15 to 150 milligrams. The labour of drying and weighing 12 or more of these filters at the beginning and end of each month is not excessive and only the usual laboratory facilities are required.

5·43 *Volumetric Sulphur Dioxide Apparatus*

At Leicester this apparatus was used in combination with the daily smoke filter. For accurate determinations of low concentrations of sulphur dioxide it was essential to use hard glass, both for the inlet tubing and the bubblers. All rubber tubing and the brass filter paper holder, whether enamelled or not, had to be waxed internally.

The apparatus determines concentrations of sulphur dioxide accurately, provided that no alkalies or other acids (stronger than carbon dioxide) are dissolved out of the air. The effect of other substances, particularly atmospheric ammonia, was discussed in Section 2·513. It was shown that if the concentration of sulphur dioxide is to be determined to within 0·005 volume per million volumes of air, a correction must be made for ammonia caught in the bubblers. On the other hand, the volumetric method, uncorrected for ammonia, may not underestimate the *effective* sulphur dioxide, i.e. the concentrations available for attack on plants, animals and materials.

The hourly volumetric apparatus is subject to the same difficulties as the standard daily apparatus.

5·44 *Lead Peroxide Method*

It was shown in Section 4·8 that the lead peroxide method is unsuitable for use in problems connected with the actual concentration of sulphur dioxide. It is particularly suitable for determining seasonal variation and trends of emission, and is more reliable than the volumetric method for these purposes. It is also more reliable, since it is not affected by ammonia, for determining the distribution of sulphur dioxide, except when actual values of the concentration are required.

There is one way in which the lead peroxide apparatus can be improved for these purposes. In Sections 2·613 and 4·83, rain was shown to increase the yield of lead sulphate, although it decreased the concentration of sulphur dioxide. Laboratory tests confirmed that this was due to the increased reactivity of a surface of lead peroxide when it is wet. If lead peroxide candles were completely protected from rain during exposure, while being freely accessible to air, it is probable that the rate of sulphation would be much less influenced by rain. This type of protection can be achieved by a louvred housing, made of a material which does not react with sulphur dioxide.

The lead peroxide method was originally designed to measure the likelihood that sulphur dioxide will cause building materials to decay. Now building materials are likely to be more reactive when wet in the same way as lead peroxide. When used for these purposes, therefore, the lead peroxide candle should be given the minimum protection against rain. A cowl is necessary, however, to prevent lead sulphate from being washed away by heavy rain.

5·441 *Directional lead peroxide apparatus.* Although they did not form part of the Leicester Survey, two instruments were set up at Station 2, University College, for tests under working conditions. One instrument consisted of a cylindrical surface of lead peroxide, of total area 250 sq. cm., covered by a cylindrical shield having one-eighth of its circumference cut away to form a window. The shield was attached to a wind vane which kept the window facing upwind. In this way only the upwind octant of the lead peroxide surface was open to the wind, and it was hoped to discover, after each month's exposure, which winds contained most sulphur dioxide. The second instrument incorporated an electrical wind recorder to measure for how long during each month the vane pointed in each of eight directions.

In use it was found that the rotors were apt either to stick or to allow too much leakage of air to the unexposed parts of the lead peroxide surface. This is a difficulty with many outdoor instruments with moving parts, and it was increased in this case by the nearness of a reactive surface. The directional lead peroxide gauge, in its present form, cannot be recommended for general use.

5·45 *Daylight Measurement*

The chief defect of the ultra-violet daylight integrator, described in Section 2·7, is that its readings are affected by variations in sensitivity of the gaslight printing paper. The normal remedy is to obtain on each print a record of a standard illumination exposed for a standard time. This device could be used with the ultra-violet daylight integrator, and the graduations would then be matched with the standard record instead of the separate standard shade which was used at Leicester.

Photographic photometry always requires extreme care and precise technique, and for general purposes a dial reading apparatus is much to be preferred. As long ago as 1930, trials were made of a photoelectric daylight counter, which made a count of one every time it received a given amount of light-energy. This instrument was unsatisfactory, chiefly because of the large variations in temperature which it suffered on exposure out of doors, but later developments in radio technique have made it worth while to try the same method again. A new instrument is therefore under construction.

5·46 *Siting of Instruments for the Measurement of Atmospheric Pollution*

The importance of choosing suitable sites for the different instruments cannot be over-emphasized. For their normal purposes, the instruments should be put where their readings will be characteristic of a large surrounding area. To achieve this for the deposit gauge requires (a) that the site is open, so that particles have a free fall to ground in the neighbourhood of the gauge (the height of adjacent obstacles should not exceed half their distance from the gauge); (b) that industrial chimneys are to be found at a similar distance in all directions from the gauge ($\frac{1}{4}$-$\frac{3}{4}$ mile is suggested for a town like Leicester); and (c) that interference by unauthorized persons is impossible. It is often difficult in practice to obtain these conditions, particularly (b). The battery of smaller gauges mentioned in Section 5·322 might be easier to arrange, because condition (b) does not apply.

Instruments for measuring smoke and sulphur dioxide are not so exacting.

Air from out of doors must be used, and the apparatus must not be too near sources of smoke and sulphur dioxide. It is probably sufficient to make sure that the instruments are never enveloped in visible smoke or in concentrations of sulphur dioxide which can be smelt.

Daylight instruments, such as the ultra-violet daylight integrator, which are sensitive to light from any part of the sky, should be placed where the horizon is as open as possible. A correction should be applied for obstructions above the horizon, and the correction formula loses accuracy if the obstructions are high or irregular. When the loss of daylight due to smoke is being measured, the instruments should be near the ground so as to be under the smoke, but should be out of reach of local smoke trails.

5·5 Information to be derived from Measurements in Polluted Areas

Local authorities and firms, as well as private individuals, make observations of atmospheric pollution. This they do for a variety of reasons, but the one reason common to all investigators is that they all recognize pollution as an evil, to be eliminated ultimately, and meanwhile at least to be held in check. It is in the public interest that everyone should know something about the general nature and magnitude of atmospheric pollution. If local observations are available, the process of public education can be much accelerated.

5·51 *Distribution of Pollution*

Townspeople want to compare the atmospheric pollution of different districts, paying special attention to the dirtiest part of their own town. The same information is needed by Health Officers, Sanitary Inspectors, Borough Surveyors, Architects and others concerned with town planning.

Smoke, sulphur dioxide, and deposited matter will normally be distributed in different ways, since they are not produced in identical circumstances. The most interesting distribution is probably that of smoke, for several reasons. Smoke is not only a maker of extra work, but it affects public health both directly and indirectly by cutting off visible and ultra-violet daylight. Moreover, smoke is avoidable and a sign that fuel is being burned wastefully. When towns are replanned or modernized, the natural outcome is a reduction of the smoke nuisance. Firstly, every attempt to relieve overcrowding leads to a more even distribution of smoke in the town as a whole. Secondly, every improvement in fuel-burning equipment should reduce the total output of smoke. With the best equipment no smoke is made at all.

The mean distribution of smoke can be measured with a number of monthly reading smoke filters, designed in accordance with the suggestions of Section 5·322. For a town of 250,000 inhabitants, about 12 instruments are required. spaced one to two miles apart, with additional instruments in districts to which special attention is being directed. One or two of the instruments should be in the country, preferably on the side of the town from which the prevailing wind blows, to estimate the lowest mean country pollution near the town. A carefully planned survey can be expected to give a useful estimate of smoke distribution in about a year; in subsequent work, abnormalities and special circumstances may be investigated.

The mean distribution of daylight, whether visible or ultra-violet, is allied to but different from the mean distribution of smoke (Section 3·491). Monthly daylight reading instruments of suitable accuracy are not yet available, however, although monthly means of daily readings would be satisfactory. Unless there is sufficient staff available to maintain a greater number of daily reading

instruments, it is recommended that two only be installed, one outside the town and one near the centre. The information from these would form a useful supplement to smoke observations.

The mean distribution of sulphur dioxide can be measured with about twelve lead peroxide candles (Sections 2·6 and 5·44). The volumetric method is less suitable for a simple survey because it requires attention at least every three or four days, but it might conveniently be used to check particular lead peroxide results. Sulphur dioxide is produced in even the most efficient coal or coke-burning appliances. Hence its distribution will be more closely related than smoke to the distribution of factories, offices and industrial undertakings.

The mean distribution of deposited matter requires a much larger number of observations, because deposited matter is much more local than either smoke or sulphur dioxide. Also, the full analysis of each sample is more laborious than either the measurement of a smoke stain or the estimation of lead sulphate in the lead peroxide method. If such a task could not be undertaken, possibly a set of small gauges, as suggested in Section 5·31, could be placed in the most industrial part of a town. Their yields need not be analysed separately, unless it became evident that there were systematic differences, when individual analyses of, say, total insoluble matter might be advisable.

A knowledge of the distribution of pollution in and near a town is a most desirable end in itself. It also brings with it a knowledge, less accurate it is true, of the distribution of emission and of combustion efficiency. The latter requires that the distribution of both smoke and sulphur dioxide is known, for it depends on the smoke-sulphur ratio. How this information may be deduced was discussed in Chapter 3. Since it has been shown that a useful knowledge of the distribution of smoke and sulphur, together with an idea of the efficiency of combustion in a town, may be obtained in the course of about a year, by using about a dozen monthly reading smoke filters and a dozen lead peroxide candles, it is to be hoped that some at least of our more enterprising cities will themselves undertake such work.

5·52 *Measurements of Variations with Time*

The standard methods which have been used or devised during the past thirty years, for investigating atmospheric pollution in Great Britain, have been mainly concerned with variations with time. In the light of experience gained during the investigation, as well as during the Leicester Survey, there are good reasons why these measurements should not only continue but be increased in variety. Suggestions have already been made in Section 5·4 of new ways in which pollution can be measured. The information to be derived from measurements both old and new is considered in the present section.

5·521 *Trends*. During wars, and periods of recovery after wars, the trend of atmospheric pollution is particularly interesting. When measures aimed at controlling pollution are relaxed we can best see what progress had previously been made. When these measures are put into force again, or when further measures are introduced, their effect can best be followed by systematic observation.

The standard instruments described in Chapter 2 are all suitable for measuring trends of pollution, except the automatic filter in its present form, for the reason stated in Section 5·421. If no information is required about short-period variations, the monthly reading instruments are preferable, and concerning these only two comments are needed. A set of small deposit gauges will give accurate information more quickly than a single standard gauge, and is to be preferred for measuring trends of industrial pollution. For measuring trends in the emission of sulphur dioxide, the lead peroxide apparatus appears to be rather more accurate than the volumetric apparatus.

5·522 *Smoke-sulphur ratio.* Either a monthly or daily reading smoke filter is recommended for measuring trends in smoke production; but if there is reason to believe that smoke is being needlessly made, the ratio of smoke to sulphur dioxide should be observed. Since even the best coal-burning open grate may be said, from one point of view, to be making smoke needlessly, it follows that the smoke-sulphur ratio is worthy of attention in all British towns.

This ratio is discussed in Sections 3·6 and 4·731. It is not unduly variable from day to day, and therefore tends to give information quickly. With certain limitations it measures the efficiency, or more properly the degree of smokiness, with which coal is being burned; but it is not selective, for it takes account of coal burned for all purposes in the square mile or more of town surrounding the point where it is measured. It is best observed by daily readings with the combined smoke filter and volumetric sulphur dioxide apparatus, described in Section 2·511.

As a test the ratio was evaluated for Leicester and Cardiff in winter. The values were 3·1 and 1·0 respectively, as milligrams per cubic metre divided by volumes per million. This result suggests that Cardiff produces about $\frac{1}{3}$ as much smoke from a given weight of coal as Leicester. Cardiff is known to be relatively smokeless, because much low-volatile coal is burned there. (See also Section 5·211.)

5·523 *The periodic cycles* give approximate information about the reasons why pollution is produced. If pollution is produced in generating power for industrial or domestic purposes, the yearly cycle will be small; if in heating dwellings, offices and factories, the yearly cycle will be large. Pollution of industrial origin, whether for heating or power, undergoes a strong weekly cycle; domestic pollution a different weekly cycle, with sometimes a maximum at week-ends. The daily cycle gives some information about our daily cycle of habits; and it is also a striking illustration of how the activities of man pollute the air and of how quickly nature repairs the damage.

If pollution depended merely on human activity, its periodic cycles would be relatively easy to understand and its irregular variation would be small. But pollution depends also on a number of meteorological factors, which vary both periodically and irregularly, and its irregular variation is in fact extremely large. The considerations of the last paragraph are therefore much over-simplified; the only circumstances when weather may be left out of consideration are in discussing the weekly cycle, since no known weekly cycle exists in meteorological phenomena.

5·524 *Irregular variation* is the only key at present to the connection between pollution and the meteorological variables. If weather could be controlled at will, and varied in one way at a time, the connection would be better understood than it is at present; but some information can be got by studying the irregular variations of pollution and weather, as in Sections 4·5, 4·6 and 4·7. Daily or hourly volumetric observations of sulphur dioxide and smoke are most subject to irregular variation, and therefore most suitable for study.

5·525 *Smoke-forecasting.* There is now enough knowledge for an elementary form of smoke-forecasting to be possible, and there are several groups of people who would like to have information in advance when unusually high concentrations of smoke are to be expected. Power stations have at present to bear an unexpected load when lights in offices and houses are switched on earlier, or off later, than usual, but they would be forewarned by a daily smoke forecast. It would also help the housewife in the choice of her washing day, since there are days when it is detrimental to hang clean linen out of doors. With the co-operation of the meteorological services it should be possible to forecast high concentrations of pollution (whether associated with fog or not), as well as

the low concentrations which accompany good drying weather. Fog forecasts are made in normal routine by the meteorological staff at aerodromes.

5·53 *Identifying Pollution*

The problem of discovering the source of a particularly high concentration or deposit of pollution can theoretically be solved under certain conditions. When a heavy deposit is noticed in a particular district, the first step is to find in what winds the deposit is heaviest. This can be done by placing four or eight deposit gauges, fitted with covers over the collecting funnels, close together on a suitable site within the district, and by taking daily observations of the wind force and direction. Each gauge should be uncovered only in a certain wind direction; a daily visit is necessary to adjust the covers. After a suitable period, which may be from two to six months, the material in the gauges is analysed. The wind direction represented by each gauge is noted, and also the number of days for which it was exposed. Results of analysis should be expressed as milligrams per square metre per day in order that the deposits in different wind directions are comparable. If the heavy general deposit in the district under investigation is due to a single source, there will be an exceptionally heavy rate of deposit in a single wind direction, and this will indicate the direction of the source. Its identity will probably be fairly clear at this stage, but may now be confirmed by moving the set of deposit gauges to another site in a different direction from the suspected source.

A similar technique may be used to identify sources of sulphur dioxide. As an exercise during the Leicester Survey, the power station was identified as a source of sulphur dioxide by means of routine daily volumetric observations. Station 2 (Fig. 3·1(b)) was $\frac{3}{4}$ mile east of the power station and $1\frac{1}{4}$ mile SSE of the centre of Leicester. The concentrations of sulphur dioxide reaching Station 2 in west winds would normally be about equal to the concentrations in north-east winds, but in practice they were found to be higher by the factor 1·38. This estimate was derived from Tables 3·45, the general mean wind directional tables. If a correction is made for the sulphur dioxide present in country air, the factor is 1·43. Station 3 was 1 mile north-west of the power station and 1 mile WSW of the centre of Leicester. By Tables 3·45, there was an average of 1·26 times as much sulphur dioxide present in south-east as in north winds. After correction for country pollution this factor is 1·42. The standard error of these estimates is about 0·07, and all the factors are significantly greater than 1·0. Hence a special source of sulphur dioxide is indicated to the west of Station 2 and to the south-east of Station 3. The conclusion for Station 2 was confirmed by the directional lead peroxide apparatus.

5·6 Future Research

In Section 5·4, suggestions were made for improvements in instruments for routine observations of pollution. Considerable work is needed on instrument design, but even more is needed to examine fundamental questions about pollution, many of which have been raised in this report.

Very little previous work had been done in the field of investigation covered by the Leicester Survey. The most closely related of all earlier work was the survey at Norwich in 1930[9], and this had a comparatively limited programme. Other observations have been begun in New York[33] and Chicago.[34] Consequently few of the conclusions in this report can be tested by comparison with previous results, and their confirmation or modification must be left to future workers. Further, a statistical investigation seldom produces results of high precision, and there may be more direct methods of particularizing some of the general statements in this report. Finally, not all problems of pollution are

best approached by a survey in and near an industrial town; other districts as well as other methods may be more suitable. The suggestions for future research which are made in the next sections have all arisen for one or other of the above reasons.

5·61 *Vertical Distribution*

Systematic observations are needed of the height to which pollution reaches. Knowledge of this height is needed in any attempt to associate the mass of pollution emitted with its concentration in the open air, e.g. in Sections 3·5 and 5·241. This is one reason for observing the vertical distribution of pollution, but there are others. For instance, the variation of pollution near the ground has led to three inferences about pollution above chimney level in this report:
(1) Smoke and sulphur dioxide do not accumulate in the air as it blows across the town in the same way as they would if the town were covered by a roof above the chimney tops (Sections 3·41 and 3·49). There is almost no cumulative effect in the surface air since in all winds the maximum concentrations are found near the centre of Leicester. Now it is inconceivable that pollution is removed by deposition as rapidly as it is added to the air blowing across Leicester, and if the added pollution is missing from the surface air it must be above the surface.
(2) Turbulence is the most effective meteorological element in controlling the concentration of smoke and sulphur dioxide. On turbulent days there is less pollution near the ground than on days of poor circulation (Section 4·71). It must be inferred that the missing pollution will be found above the chimneys.
(3) On windy days there was almost as much pollution near the ground in Central Leicester as on days of light winds (Section 4·71). This is a remarkable result, which has not yet been fully explained. But if it is true, then near the ground on windy days there must remain pollution which in lighter winds would have diffused above the chimneys. Thus there should be less pollution above the chimneys in central Leicester on windy days than on days of light winds. This is not unreasonable, since on windy days there is less time for pollution to diffuse upwards before it passes the centre of the town.

It is evident that pollution needs to be investigated up to considerable heights, probably several thousand feet. A three-dimensional survey over a town such as Leicester would be a very large undertaking if it were to include these heights, but much useful information could be obtained with a more limited investigation. To begin with, it is suggested that observations be made during one or two winter months at places such as the Eiffel Tower (or Blackpool Tower). The concentration of smoke and sulphur dioxide should be observed hourly at suitable heights, for instance 0, 50, 100, 200, 400, 700, 1000, 1500 feet. A combined form of smoke filter and volumetric sulphur dioxide apparatus would be suitable; it is doubtful whether existing automatic apparatus would be able to deal with the large volumes of air required, and continuous supervision by an observer is to be preferred. Because of the daily cycle of turbulence, however, it is important that observations should be continued throughout the day and night. Collateral observations at each height should include air temperature, hourly wind run, and wind direction. Observations of relative humidity and visibility might help to decide to what extent visibility is limited by smoke and by water condensates.

From a series of observations of this nature, tests could be made of inferences (2) and (3) above. When there is little pollution at the surface because of turbulence, there should be more pollution above the surface; and when the surface pollution is nearly normal in spite of moderate to strong winds, there should be little pollution above the surface. Hourly determinations could be made on the height above which concentrations are less than one-tenth of

surface concentrations; this height should vary directly with turbulence and inversely with wind velocity.

Inference (1) could be tested, but not thoroughly investigated, by a similar series of observations on a second mast near the edge of a town. It would be expected that high up the mast there would be large differences in pollution according as the wind blew towards or from the town. When the total smoke in a vertical column of air is considered, less smoke should be found at the centre of a town than one mile or so farther downwind (Section 3·491). Observations with two or more masts would test this statement in suitable directions of wind. An easier though less direct way would be to observe the total absorption and total scattering of light from vertical beams. This could be done at night with telephotometers. Observations could also be made during daytime of the apparent brightness of the zenith sky. On the whole, inference (1) is considerably harder to test than inferences (2) and (3).

5·62 *Research on Country Pollution*

It is known to be easier in the country than in towns to keep buildings, furniture, and clothing clean.[29] A knowledge of the amount of pollution in country air is therefore desirable. Information about country pollution is to be found in the Annual Reports of the Investigation of Atmospheric Pollution[1], but this is confined to results with the deposit gauge and the lead peroxide method, and there are too few observing stations to represent the whole countryside. Observations of country smoke can conveniently be made with a monthly reading smoke filter (Section 5·422). Any town which proposes to study pollution at all thoroughly should not be content with observations within the town but should also have at least one country station. Without a knowledge of country pollution, measurements of the pollution in towns are necessarily incomplete.

The variation with wind direction of country pollution near Leicester was well marked, and was interpreted in Section 3·47 as the effect of distant densely populated areas. There are other country places in Great Britain where even greater variations with wind direction are likely, such as central Yorkshire and Lincolnshire, the coast of Lancashire, and almost any country district within 30 miles of London. Observations in any of these districts would be particularly interesting, and would test the conclusions of Sections 3·47 and 5·22.

There is also the world-wide geophysical aspect of atmospheric pollution, which can be investigated by measuring the pollution in the air as it enters and leaves the British Isles. Observations in Cornwall and western Scotland could be used to investigate, for instance, whether equatorial air is more or less polluted than polar air. Meteorological information is accurate enough to decide when the air masses reaching this country are likely to have passed through industrial regions of Europe or America. The additional pollution in such air masses will give evidence about the time required for pollution to be removed from the atmosphere.

5·621 *The heights reached by country pollution* are likely at times to be much greater than the height of the denser pollution over towns. It is true that when the temperature gradient is positive over the whole countryside, pollution may drift far horizontally without undergoing much vertical diffusion, and observations below 1000 feet may be very informative. But at times of strong vertical circulation there is no reason why pollution should not diffuse up to the tropopause, becoming much attenuated in the process. Measurements in an aeroplane up to a height of 40,000 ft. would then be needed. The low concentrations of pollution, and the short time available for taking samples, suggest that a quite different method of estimation should be used. For smoke, the most convenient instrument would probably be some form of ultramicroscope, wherein

a sample of air is let into a chamber and the solid particles are made visible by strong illumination and counted. For sulphur dioxide a delicate micro-chemical or spectroscopic technique would need to be developed.

5·63 *Research on Natural Removal of Pollution*

There is little doubt that nearly all the particles of pollution which are large enough to fall to earth in a few minutes are removed by deposition, and much of the material collected in deposit gauges is of this type. But the mechanism whereby air is cleaned of fine smoke particles and sulphur dioxide is not yet fully understood. Three distinct ways of removing smoke and four ways of removing sulphur dioxide have been suggested. These are for smoke: (a) by attachment to cloud particles which afterwards fall as rain or snow, (b) by attachment to falling drops of rain or crystals of snow, and (c) by deposition from the minute wind eddies set up by vegetation and other obstacles. The four ways of removing sulphur dioxide are: (d) by solution in cloud droplets which afterwards fall as rain, (e) by solution in falling drops of rain, (f) by reaction with the ground and building materials, or by solution in water on these surfaces, and (g) by reaction with other forms of pollution such as ammonia, followed by removal. On an average over the earth as a whole there can be no doubt that both smoke and sulphur dioxide are removed at the same rate as they are produced. It is therefore of interest to find which of the above processes remove most pollution, and whether any other processes operate. In this report, reasons have been given why processes (a) to (f) seem likely to be important. Little is known about (g).

Investigation into (a), (b), (d), and (e) appears to be a matter of taking samples. Cloud-water and cloud-ice can be collected by aeroplane, though care will be needed to avoid making new ice or water in the act of taking samples. When this difficulty is overcome, samples large enough for chemical analysis should be easily obtainable. There has been a little pioneer work on the pollution of falling rain, though conclusive deductions have not been put forward. One fact has been observed which is particularly interesting: the early part of a shower frequently brings down more dissolved matter than the later part. The reason for this is not known at present. The dry air beneath the clouds may contain some very soluble constituent which is rapidly dissolved in the early drops of rain; or the early part of a shower may have had the longest life, in liquid form, within the cloud. Evidently a systematic collection of samples from falling rain is needed before these questions can be answered.

The first examination of suggestion (c) should perhaps be a qualitative one. If smoke is deposited by eddies on dry vegetation, it will be necessary to make some chemically clean inert material having the structure of grass, and to expose this to the wind. The rate of emission of smoke during winter in a town might be 100 milligrams per square metre per day, and a square metre of the material might collect about 10 milligrams per day. A high standard of experimental accuracy will therefore be needed. If process (c) is an important method of removing smoke from the air, this will mean that the ability of an object to collect smoke is affected by its shape and size. It will then be necessary to consider how effective the deposit gauge is as a collector of smoke, and to reconsider Section 5·241, on the average life of smoke particles.

Suggestion (f) is difficult to investigate because of the variety of materials which make up the earth's surface. However, the commonest of all is water, and the first step should be to examine how quickly sulphur dioxide is taken up by water. If sulphur dioxide dissolves readily in surface water, not only the oceans but the general dampness of the ground after rain or dew will be effective means of removing it. It is not difficult to expose dishes of water, and after-

wards to estimate the dissolved sulphur dioxide by titration. The concentration of sulphur dioxide in the air should be observed at the same time. Experiments of this kind would lead to a rough estimate of how quickly the surface water of the world is withdrawing sulphur dioxide from the atmosphere.

If ammonia is the only other form of pollution likely to react with sulphur dioxide, suggestion (g) can be reduced to a single question. The air is known to contain small quantities of the sulphur oxides, either free or in solution; it also contains ammonia and carbon dioxide, and possibly higher compounds of ammonia, carbon dioxide, sulphur oxides, and water. The question is, What proportion of the total sulphur is combined with ammonia? The answer will be most readily obtainable when a way is found of withdrawing the above compounds from the air one or two at a time. Research on these lines would be the first step towards testing suggestion (g). It would also aid the interpretation of results by the volumetric method (Section 2·513), because the presence in the air of variable quantities of ammonia may be a serious hindrance to exact determinations of atmospheric sulphur dioxide, particularly in country districts.

5·64 *Research on Atmospheric Turbulence in its Association with Pollution*

The observations made at Leicester of lapse rate, wind gradient, and other measures of turbulence could not be expected fully to elucidate the connection between suspended pollution and turbulence. The observations were confined to one range of heights, 5 to 10 metres, and to one site, over pasture land at Station 9. But it is known that turbulence varies with height, and also with type of surface. Evidently, in considering the pollution in a town, some measure of the mean effective turbulence in a large volume of air is needed.

The immediate objective of research should be to find a measure of turbulence which is closely connected with the pollution of a town. Between 13 h. and 16 h. the emission of pollution is at its steadiest, and it would be preferable to confine observations to this time of day. The effect of variable wind should be avoided by making observations only in a definite small range of wind velocities, and, if necessary, only in certain wind directions. However, if sites could be found where the concentration of pollution is independent of wind direction, the investigation would increase very much in speed. Measurements should include: concentration of pollution at a group of sites near ground level and chimney level; temperature and wind velocity at a series of heights up to at least 100 ft., at the same sites; visual observations on smoke trails from chimneys and on standard artificial smokes; observations with a bi-directional wind-vane, which shows changes of direction in a vertical as well as in a horizontal plane. It is not easy to foretell the success of an investigation of this kind, but it appears to be the most likely way of approaching the problem. If the rate of emission of smoke in a town is sufficiently constant during a series of afternoons, a reasonably accurate relation between smoke concentration and turbulence should be found. If a constant "natural" area source of smoke is not obtainable the difficulties of the investigation will be much increased, for the alternative is to generate artificial smoke from standard sources distributed over a large area. This would not only require a costly organization, but it might be a social inconvenience.

5·65 *Atmospheric Pollution in Parks*

There is good reason to believe that information about turbulence, and its effect on concentrations of suspended impurity, can be got from measurements of pollution in parks. Fig. 3·71(a) shows how the contamination of Hyde Park with smoke from surrounding districts appeared to depend strongly on the very

same factors which produced the irregular day-to-day variation of smoke concentration. When these factors reduced the town concentration of smoke below normal, the concentration at the cleanest part of the park was even farther below normal, but when there was much smoke in the town air there was almost as much in the park. The concentrations of smoke and sulphur dioxide in towns vary very much from day to day (Fig. 4·5), but in central parks they appear to vary even more. If the range of variation in the centre of a town is 10 to 1, the range in a central park will be of the order 100 to 1. This is much greater than the effect of the yearly or weekly cycle, or of random variations in human activity, and a single observation of smoke or sulphur dioxide in a central park should be a good guide to the degree of turbulence and similar factors affecting the concentration of pollution. A still better guide would be the ratio of the concentration in a central park to the concentration immediately upwind from the park.

The measurements in Hyde Park were few, but they quickly brought to light matters of great interest. To investigate these matters thoroughly, the following observations are desirable: hourly readings of smoke and sulphur dioxide concentrations north, east, south, and west of a park and at three points near the centre of the park; hourly readings of wind direction and velocity; hourly readings of vertical gradients of temperature and wind velocity, and also of other possible measures of turbulence. The first step in working up such observations should be to make a curve similar to Fig. 3·71(a), showing the relation between contamination of the park and pollution upwind from the park. By means of this curve, the daily and yearly cycles of pollution could be calculated, as they would be if there were no daily or yearly cycles in the emission of pollution. The cycles in the emission of pollution could then be estimated by difference. Other tests could be made of the information to be obtained from individual observations in the past.

One difficulty which may reduce the accuracy of this work is that at night, when there is little pollution of local origin, there may still be considerable exotic pollution. There will be a tendency for the upper air to contain nearly as much exotic pollution as the surface air, and the advantages of vertical mixing will be lost. In the case of exotic pollution, therefore, the contamination of a park will always be nearly 1·0, whatever the degree of turbulence. Probably the easiest way to deal with this difficulty will be to avoid observations in wind directions which are likely to contain much exotic pollution. In 10-m.p.h. winds, night observations will be most affected by industrial districts 30 to 120 miles away. London is therefore a suitable city for this work, especially if north-west winds are avoided.

If a fairly reliable curve similar to Fig. 3·71(a) can be obtained, it will follow that a number of investigations which require a steady area source of pollution can be made with the help of observations in central parks. Much of the difficulty in understanding the variations of atmospheric pollution has been due to our inability to control its emission at will. It now seems possible that observations in central parks will yield the same information as could be got from controlled emission of pollution.

5·66 *Research by Local Authorities*

Most of the items of future research suggested so far would require the full-time attention of a special staff. However, there is much research which could better be undertaken by interested Local Authorities or individuals, because it requires local knowledge and is not necessarily a full-time occupation. In the past, much has been done by Local Authorities in the field of research on atmospheric pollution, as well as in the taking of routine measurements. The following is a summary of additional work which could be done:—

(1) a simple survey with monthly readings of sulphur dioxide, smoke, and deposited matter.
(2) observations near the centre of the town of the weekly cycle of smoke and sulphur dioxide.
(3) special observations in a central park, to show how extremely variable is the smoke and sulphur dioxide to be found there, and to show how much less insoluble matter is deposited at the centre than near the edges of the park.

Details of the observations necessary for (1) and (2) are to be found in Section 5·5. Information about (3) appears in Sections 5·65 and 6·2.

6·0 APPENDICES

6·1 Statistics

6·11 *Introduction*

There is an important difference between studying phenomena where all the conditions are under the experimenter's control and studying other phenomena where many of the conditions affecting the result are not under his control. The difference will be made clear by considering, say, (a) the solubility of ammonia gas in water at different temperatures and (b) the rate at which ammonia gas is removed from the atmosphere by rain. In the first case a good experimenter will obtain such consistent results that, if he draws a graph plotting dissolved ammonia against temperature, all his points will lie closely on a smooth curve; and *however often he repeats the measurements the points will always lie on the same curve.* In the second case the experimenter will have to measure the amount of ammonia in the air before and after rainfall, or the amount of ammonia found in the rainwater. Here many conditions affecting the result are not under the experimenter's control, and, however good an observer he may be, when he plots dissolved ammonia against rainfall his points will be scattered in a band across the diagram; while if he makes similar observations on another occasion, the plotted results will show differences from the former measurements. This is because the rate of rainfall, size of raindrops, and other uncontrollable conditions affect the results.

Much can be inferred, however, from observations of uncontrolled phenomena. A new technique has been developed, chiefly in the last fifty years, for dealing with such observations. It is called the statistical theory, and, because it is quite different in outlook from the precise scientific method, the present note has been written about some of the ideas in it. The essential difference is that probability instead of certainty is the central question. Take the proposition "The west coast is wetter than the east coast." If we observe for a few days at a time the weather on the two coasts we shall very likely find more wet days in the west. But on some days the opposite will be true. So we might draw the wrong inference if we rely on chance selection of the days on which observation is made. To be more sure we should set up permanent rain gauges in the two places, and at the end of the year the difference in readings would make us fairly sure, though even then there may be exceptional years when the opposite result would be got. After taking longer and longer observations we should be more and more sure, but the comparative certainty of the laboratory experiment is never attained.

The science of statistics is the method of handling such problems. The observations made always consist of a *sample* out of a total that could be made, and the aim is to deduce from this sample what can be inferred about the whole. The bigger the sample the more certain the inference, but economy of labour calls for the use of as small a sample as is admissible. Statistical theory tells how large the sample must be for inferences to be drawn with assigned degrees of confidence. Absolute certainty is never attained, but statements can be made like "You are maintaining that the east coast is as wet as the west. From my observations I can say that if you are right, then I was very unlucky in the days when I made them. The chances against what I found were 20 to 1 on your hypothesis. You may be right, but on this 20 to 1 basis it is much simpler to believe that the west coast really is wetter than the east."

(The above statement is more carefully worded than might appear. Its author was wise in trying to prove his opponent probably wrong, rather than himself probably right, though in the end the two propositions mean the same thing. The reason is that the opponent's proposition commits itself more. It claims, in effect, that the difference in the average rainfalls is 0 mm. per day. The alternative proposition would claim that the difference in rainfall was some unspecified number other than 0. This has an important bearing on the idea of significance which is discussed in Section 6·12.)

The Leicester Survey belonged to the class of investigation where many of the relevant details could not be controlled. The general method was to make regular observations of all the meteorological variables which might be relevant, and, when a suitable number of observations had been collected, to apply the statistical technique to discover which of them had a bearing on atmospheric pollution. The results of this investigation were given in Chapters 3 and 4, where it was often necessary to refer to statistical terms and principles. A few notes are therefore given in the next section about the commoner aspects of statistics.

6·12 *Statistical Terms and Principles*

Before a statistical investigation can begin, a large number of observations must be collected. From these observations the statistician will try to draw conclusions about the amount and cause of the variations in them. The way he goes to work can best be seen by considering a definite example. The example chosen is concerned with an atmospheric impurity, ammonia; but since suitable observations are not at present available, hypothetical observations have been invented.

Suppose Fig. 6·12(a) represents the daily concentration of ammonia gas on 43 weekdays of July and August, 1938. This diagram was made by putting a dot each day in the column which included the (hypothetical) daily concentration of ammonia. The concentration is expressed in arbitrary units. Fig. 6·12(b) represents the (actual) daily rainfall in the same two months, the diagram having been constructed in the same way as Fig. 6·12(a). Evidently (a) and (b) are very different in their *distribution*. Any sort of distribution is possible, but some types are more prevalent than others, and the two here illustrate two very common types. Type (a) is called a *normal* distribution and (b) resembles what is called a *Poisson* distribution. The statistician has his own ways of testing whether any given set of observations conforms to either of these types or to any other different type. Type (a) is the commonest, and the observations considered in this report frequently approximate to it. This is fortunate, because there are many statistical methods and ideas which have been worked out only for normal distributions.

The mean of a set of observations is well known to be the sum of all the observations divided by their number. The mean of the daily concentrations of ammonia in Fig. 6·12(a) is a little over 100 arbitrary units, and is marked by the thick line. The mean rainfall during the same period was 0·1 inch per day.

The variance is a very useful measure of the variability of a set of observations. It is defined as

the sum of the squares of all the differences from the mean,
divided by
the number of observations in the set, minus one.

The variance of the ammonia concentration in Fig. 6·12(a) works out to be about 450 (arbitrary units)^2. If the ammonia concentration were more variable, perhaps occasionally rising to as much as 200 units, and falling to as little as 20 units, then the figure 450 would be considerably increased. The variance of daily rainfall in diagram (b) was 0·02 (inch per day)^2.

The standard deviation of a normal set of observations is the square root of the variance. It has the advantage that it is in the same units as the observations themselves, but for mathematical reasons it is usually restricted to normal distributions. The standard deviation of the daily concentration of ammonia is about 21 units, and dotted lines at this distance from the mean value are marked in Fig. 6·12(a). Distribution (b) has no true standard deviation, but the square root of the variance is marked with a dotted line. The standard deviation lines are always at the same relative position in diagrams such as (a).

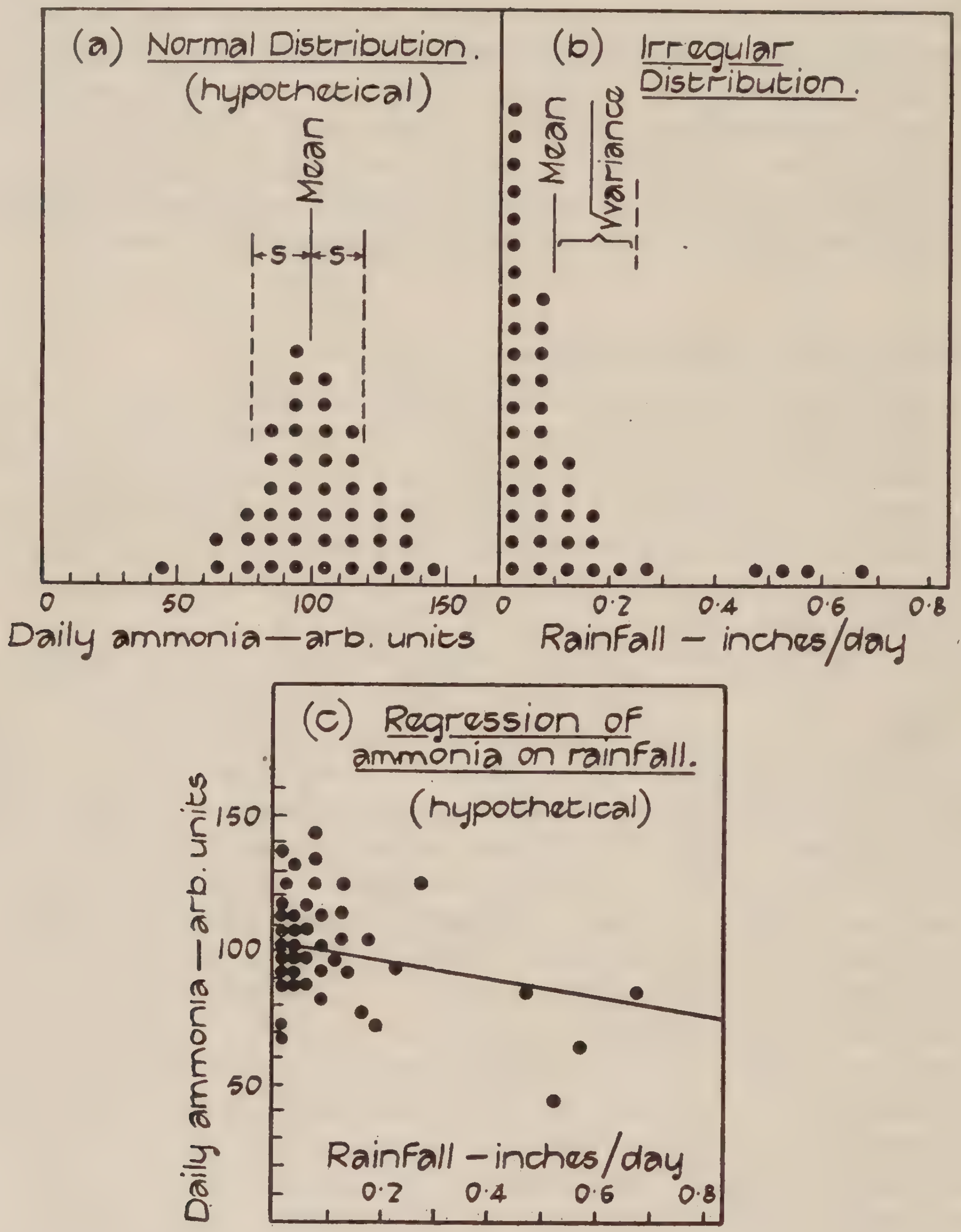


FIG. 6·12.

In fact, if s is the standard deviation of a normal distribution, differences from the mean (without regard to sign)

greater than	s	will occur about once in	3 observations
,, ,,	$2s$	,, ,, ,, ,, ,,	22 ,,
,, ,,	$3s$	,, ,, ,, ,, ,,	370 ,,

These statements will be seen to be consistent with diagram (a). Standard deviation is sometimes used as a measure of *dependability*, especially in the classical kind of experiment where the conditions are controlled. In this report, however, it is not used as a measure of dependability, but (like variance) of *variability* of the observations due to changes in conditions. Dependability is measured by tests of significance, which will be discussed later.

It is sometimes convenient to refer by the word *statistic* to any numerical measure of a property of a set or sets of observations. Thus the mean is a statistic, and so are the variance, standard deviation, regression coefficient and correlation coefficient. Repeated estimates of a statistic are liable to differ from one another, just as repeated measurements of any other variable, because they are made with different samples from the whole population. The *standard error* of any statistic is the standard deviation of sampling of that statistic. It can be calculated from a single sample if the parent distribution is normal. Thus for example, the standard error of the mean can be estimated from the same data as the mean. Formulæ for calculating standard errors are given in the books referred to at the end of this appendix.

Reverting to the example of Fig. 6·12, suppose a statistician is asked to test whether there is appreciably less ammonia on rainy days. He can examine the original notes from which diagrams (a) and (b) were made, and can plot the daily ammonia against daily rainfall on another diagram. This might look like Fig. 6·12(c). The problem before the statistician is to interpret diagram (c), and decide whether it really shows any tendency for low concentrations of ammonia to occur on rainy days. He may now construct the straight line shown in the diagram, which is the best* straight line for deriving the most likely concentration of ammonia on a day when the rainfall, but not the ammonia, had been measured. It is called a *regression line.* If this line has an appreciable inclination to the axis of rainfall, the statistician will conclude that the ammonia depended on the rainfall. Clearly no further progress can be made in this direction until an exact meaning is given to the word "appreciable." This is done below, in the paragraph on "significance," where the conclusion to the problem is also given.

The regression coefficient of ammonia on rainfall is the slope of the line in Fig. 6·12(c). It is about – 40 units per inch of rain. If there had been a tendency for high concentrations of ammonia to occur on rainy days the regression would have been positive, perhaps +40 units per inch of rain. Regression coefficients like these can be calculated from the original data without the aid of a diagram. The formula for calculating regression coefficients is given in the books referred to at the end of this appendix.

The correlation coefficient is an alternative way of testing whether there is any connexion between variables—e.g. whether the concentration of ammonia is connected with the rainfall. It is calculated by a formula similar to that of the regression coefficient. In effect, the correlation coefficient between ammonia and rainfall determines how much the variance of ammonia would diminish if there were no day-to-day variations in rainfall. The fractional reduction in variance is equal to the square of the correlation coefficient.

The correlation coefficient is always between – 1 and +1; it is negative if an increase in one variable tends to accompany a decrease in the other, otherwise it is positive. A coefficient of +1·0 or – 1·0 represents perfect correlation, and if one variable is plotted against the other all the points then lie on a straight line. When there is no connexion between the variables, the correlation coefficient is always found to be near to zero. The data of Fig. 6·12(c) yield a correlation coefficient of – 0·24; the fractional reduction in variance is $(-0{\cdot}24)^2$, i.e. 0·06, or 6 per cent. Therefore the variance of the concentration of ammonia would have been reduced from 450 to about 420 (arbitrary units)^2, if daily rainfall had remained constant during July and August, 1938. (The method of correlation is valid if at least one of the correlated variables has a normal distribution; since the concentration of ammonia is of normal distribution, the method is valid in the example given.)

Just as the method of regression reaches a stage where a definition must be

* The "best" straight line is here defined as the line for which the sum of the squares of the deviations of all the points from the line is a minimum.

given to the word "appreciable," so does the method of correlation. Is a reduction of 6 per cent. in the variance of a set of 43 observations appreciable, or not? The answer depends on the meaning given to the word "appreciable," and in the language of statistics the word "significant" is used instead of "appreciable" to indicate that it has a precise numerical meaning.

Statistics is based on probability, and all its conclusions are only probably right. This being so, the scientist is anxious to know how probable it is that his statistical conclusions are right. From Fig. 6·12(c) there seems to be some truth, perhaps not very much, in concluding that there is less ammonia than usual on wet days. By calculation it can be shown that there are eleven chances out of every hundred that this statement is not true; i.e. if figures like Fig. 6·12(c) were made by leaving the ammonia observations to pure chance, out of every hundred, eleven would have lines with more slope, up or down, than that actually given. The statement is said to have a *significance level* of 11%. (Note the inversion of idea, whereby a result of significance level 1% is more probably true than a result of significance level 2%. This is because there is no direct way of calculating the probability that the statement is true, and it is linked up with the paragraph in parentheses near the end of Section 6·11.)

The significance level of a result, therefore, is an answer to the question "How likely is this result to be false?" It often happens that such a question is difficult to answer, but it is nearly as satisfactory for the scientist to know "Is it worth investigating further?" and this question is easier in practice. Experience has shown that, on the evidence of results alone, a conclusion justifies further investigation if its significance level is 5% or better (i.e. 5% or less). This is merely an empirical conclusion, but it is so commonly accepted that it has placed a special meaning on the word "significant," thus:

Significant: having a significance level of 5% or better,

Not-significant: having a significance level of worse than 5%.

In the example, the observations of ammonia were supposed to be properly made at the same time as the observations of rainfall. Now suppose that each in turn of the 43 observations was drawn out of a hat and attached indiscriminately to one of the rainfall observations. If the hat process were repeated a large number of times, a number of figures similar to Fig. 6·12(c) could be drawn, each having its own regression line. Some of the lines would go up, some down, and the majority would be nearly horizontal. The regression is regarded as significant if the observed slope is steeper than that of nearly all (95%) of the lines from a large number of draws from the hat.

It is now possible to state in either of two ways the conclusion that on wet days there is no "appreciable" reduction in ammonia: (i) the regression of daily ammonia on daily rainfall is not-significant or (ii) the correlation between daily ammonia and daily rainfall is not-significant. In each case the significance level is 11%, which is considerably worse than the critical value of 5%. These results in themselves would not justify further investigation of the question; but if there were other reasons for believing that a connexion existed—e.g. if ammonia were found dissolved in rainwater—then a further investigation, involving more months of record-keeping or new methods of working-up, would be justified.

This concludes what is literally an introduction to the less mathematical principles of statistics. Its chief justification for inclusion in this report is to prevent any misinterpretation of technical phrases, particularly those involving the idea of significance. Further information about statistics may be found in "Statistical Methods for Research Workers," R. A. Fisher (Oliver and Boyd, 1936); also "The Methods of Statistics," L. H. C. Tippett (Williams and Norgate, 1931), "The Principles and Practice of Field Experimentation," G. Wishart and H. E. Sanders (Empire Cotton Corporation, 1938), and "An Introduction to the Theory of Statistics," G. Udny Yule and M. G. Kendall (Charles Griffin and Co., 12th edition, 1940).

6·2 Distribution of Deposited Matter in Hyde Park

By J. H. Coste, F.R.I.C., F.Inst.P.

Eighteen leaves of *Aucuba japonica*, designated by numbers only, were received, each in a cellophane envelope. They were gathered between 2.30 and 5.30 p.m. on 5th April, 1943, by Dr. A. R. Meetham, who was himself examining the air by means of a smoke filter as described in the main report (Section 3·71). There had been extremely little rain for the previous month, the last rain having been on 1st April. The wind at time of collection was WSW, force 4. They had been taken from the upper part of the plant, as the lower leaves were very muddy. Care was taken to select only leaves which were approximately horizontal.

Naked-eye inspection of the leaves after cleaning showed most of them to be in a very poor condition, with blackened dead areas. The following table shows this:—

Table 6·2(a)

Leaf No.	Colour	Leaf No.	Colour
1	B	13	*B*+ G
2	G	14	G+ *B*
3	B + G	15	*B*+(G)
4	B + G	16	*B*+ G
5	G	17	*B*+ G
6	B + G	18	*G*+ B
7	G	19	G+(B)
8	G	20	G+ B
9	G	21	B+ G

B = Black, G = Green, *B* or *G* = much, () = little.

In order to obtain the deposited matter for examination, the upper surface of each leaf was brushed with a small sable brush, and at first it was sought to weigh the matter so obtained. Since No. 1 gave only 0·5 mg. of deposit and Nos. 2 and 3 less than 0·1, it was decided to wash each leaf with the wet brush and to bring the washings into a small drawn-out glass tube sealed at the bottom, allow to stand in a vertical position for two hours, or longer, and then to cut off the drawn-out closed end, measuring the height of the deposit and the cross section of the tube; the cut-off end was used again after an experiment by joining it to its original drawn-out part by a short piece of bicycle valve rubber tubing, bringing the cut edges close together to avoid deposition on the upper edges of the little tube. It had been found that a graduated centrifuge tube, such as is used for measuring the dirt in milk, was too coarse for measuring these deposits; facilities for constructing smaller bore centrifuge tubes were not available, and the difficulty of removing the deposit for examination would have remained.

Sedimentation was incomplete and a cloudy top liquid always remained. This slowly deposited more matter, but this was assumed to be soot which had coagulated and fallen out from suspension.

The suspended matter was transferred to a microscope slide by inversion over the slide on which a drop of water had been brought. The deposit usually settled easily on to the slide, but in some cases it was stirred up with a platinum micro-spatula before inversion.

Examination of the wet deposit by transmitted light with crossed Nicols showed whether sand were present (most fibres also were illuminated under crossed Nicols). The cover glass, if one was used, was then removed and the slide allowed to dry. The dried edge of the drop sometimes showed minute crystals, indicating the presence of some soluble matter in the deposit.

In the examination of dusts I have found that the constituents of dry dust illuminated by a horizontal beam from a "bull's eye" are more easily identified

than with any other illumination and, since both coal and coke are black, a piece of green paper under the slide affords a background which shows up everything better than a dark field. An eyepiece micrometer enables particules to be measured.

It was found that swabbing the scrubbed leaves with wads of cotton-wool brought off more soot shown as a grey to black stain on the wool. The deposit seemed to be more obstinately attached than that found on leaves of the ordinary green laurel in my country garden—probably owing to the presence of more tarry matter, or possibly to a difference in the surface of the leaves of the two plants.

No great qualitative differences were observed in the deposits, nor was there any marked difference in the prevalent size of particle. All were seen to contain many particles less than 10μ and a few above 100μ in diameter. Charred wood particles were often longer than 100μ but narrow. In most cases coke was found in large amount.

Spherical particles were present in all samples, evidence of ash emitted at high temperatures. The coke spheres (cenospheres) also indicate high combustion temperature and high velocity of discharge of chimney gases. No spheres or other particles of magnetite were found. These are usually found in

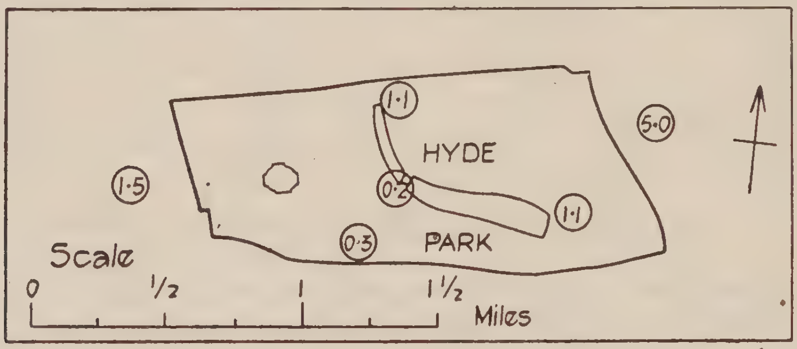


FIG. 6·2 DEPOSIT ON LAUREL LEAVES IN HYDE PARK, APRIL 5, 1943.

Apparent volume of wet deposit in mm.^{3} per 50 cm.^{2} of leaf. The deposit was washed off with a wet brush, and its volume measured after sedimentation.

ash from high-temperature furnaces (the fusion point of Fe_3O_4 is 1,580° C.; the transition point $Fe_2O_3 = Fe_3O_4$ is 1,600°C.). Magnetite has a density of 5·18 and is therefore likely to be deposited nearer the source than other constituents of ash of which the densities are in the region of 2 to 3.

The proportion of charred wood found can hardly be due to kindling. Either park bonfires or the greater use of wood fires due to the coal shortage may account for it.

The results of examination of individual leaves or of groups taken in the same place (see Table 6·2(b)) yield little evidence to show that most of the grosser suspensoids have been deposited in places in the park relatively near to their source, or that selective deposition of different kinds of suspensoids has occurred in the region examined. The results generally indicate that much solid matter from both domestic and industrial fires reaches all parts of the park. Nevertheless, there is marked quantitative evidence that in the centre and on the south side the deposit on leaves is less in amount than at places north and west, and much less than on the east (see Fig. 6·2).

In any further work on these lines it would be desirable to examine more, say five, leaves from each place, even though the work were lessened by mixing the measured deposits for examination under the microscope. The amount of deposit from each leaf should in such case be measured in order to compute the standard error.

The volumes of deposit obtained by sedimentation were referred to an imaginary standard leaf of 50 cm.^{2} area, which appeared to be the median area.

of the 18 leaves examined on the assumption that the area of a leaf was $\frac{3}{4}$ that of the containing rectangle. They afford only a very rough measure of the relative amounts of deposit on individual leaves, which obviously are seldom spread horizontally on the stems.

Some leaves from green laurels in gardens at a village two miles east of Horley (Surrey) were examined for comparison. They showed less evidence of results of combustion and more of mere soil contamination.

TABLE 6·2(b) *Examination of Deposits removed from Leaves of Aucuba Japonica collected in and around Hyde Park and Kensington Gardens on 5th April* 1943

mber of leaf	1	2	3	4	5	6	7	8	9	13	14	15	16	17	18	19	20	21	a	b
res	+	(+)	(+)	(+)	(+)	(+)	+	+	+	+	+	+	+	(+)	+	+	+	+	–	–
ssy	+	(+)	(+)	(+)	(+)	(+)	+	+	+	?		+	+	(+)	+	+	+	+		
aque, bubbly	–	–	–	–	–	(+)	+	+	–	+		+	+	(+)	+	+	+	+		
xe	+	(+)	–	(+)	(+)	(+)	+	++	+	+		+	+	(+)	+	+	+	+		
agnetic ..	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–		
red Particles	+	–	–	–	–	+	+	+	+			+	–	+	+	+	+	+	–	–
ssy	+	–	–	–	–		+	+	–			–	–	–	–	–	–	–		
aque, bubbly	–	–	–	–	–		+	+	+			+	–		+	+	+			
agnetic ..	–	–	–	–	–		–	–	–			–	–	–	–	–	–	–		
ular Particles	+	++	+	+	+	+	+	+	+	+	+	++	++	++	+	+	+	+	+	+
ke	++	+	+	++	++	+	++	++	++	+	+	+	+	++	++	++	(+)	++	+	+
al	+	–	–	+	+	+	+	+	–	+		+	+	–	+	(+)	(+)	+	+	
agnetic ..	–	–	–	–	–	–	–	–	–	–		+	–	–	–	–	–	–		
h and soil ..	?	+	+	+	+	+	+	+	+			+	+	++	++	++	++	++		+
nd	+	+	–	+	+	+	+	+	+		+	+	+	+	+	+	+	+	+++	+++
es	+	++	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	
xtile ..	+	+	–	+	+	?	?	?	+	?	?	+	?	(+)			+	+		
ant hairs or tissues ..	+	+	+	+	+	+	+	?	+			+	+	+	+		?	?	+	
arred wood	–	+	(+)	(+)	+	+	+	+	+		(+)	+	+	+	+	+	+	+	+	
arent volume wet deposit 1 leaf of cm.² ..	* 0·5	* <0·1	* <0·1	1·4	1·0	1·0	2·8	mm.³ 1·7	0·5	0·5	0·3	0·2	0·4	0·6	2·2	0·4	1·5	2·6	* 1·0	* 5·5
age ± std. error ..	0·2±0·16			1·1±0·14			5·0±3·5			0·3±0·09			1·1±0·57			1·5±0·63				

NOTES

Leaves gathered on 5th April, 1943, between 2.30 and 5.30 p.m. (Double Summer Time).
Wind WSW, force 4.
Extremely little rain for previous month.
Last rain, 1st April, 1943.
1 2 3 Serpentine Bridge, N.E. side.
4 5 6 Hyde Park Corner, well inside park.
7 8 9 Grosvenor Gardens.
13 14 15 Albert Memorial, well inside park.
16 17 18 Lancaster Gate, well inside park (north end of Serpentine).
19 20 21 Vicarage Gate and Gloucester Walk.
a and *b* green laurel leaves from gardens at Smallfield, a village near Horley.
a about 40 ft. from road and 30 ft. from house. Leeward of fairly recent bonfire.
b from hedge to road.
+ indicates present, – not found, ++ much present, ( ) very little, +++ preponderance, * weight in mg.

TABLE 6·3 *Monthly Weather Tables for Leicester during the Survey*

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Ye
Days with thunder													
Normal	0·1	0·1	0·4	0·5	1	2	2	2	0·7	0·5	0·0	0·0	1
1937 ..	0	1	—	—	—	—	1	1	0	1	0	0	—
1938 ..	0	0	0	0	0	1	2	3	1	0	0	0	
1939 ..	0	0	0	0	0	2	5	7	0	0	0	0	1
Days with snow													
Normal	4	2	4	2	0·2	0·0	0·0	0·0	0·0	0·2	1	4	1
1937 ..	3	1	—	—	—	—	0	0	0	0	0	7	—
1938 ..	1	2	0	1	0	0	0	0	0	0	0	9	1
1939 ..	6	0	3	0	0	0	0	0	0	0	0	1	1
Days with rain or other precipitation													
Normal	14	13	14	13	14	12	14	16	12	17	15	16	17
1937 ..	25	22	24	15	16	12	13	8	11	11	9	15	18
1938 ..	16	9	4	4	9	9	21	15	14	18	16	22	1[illegible]
1939 ..	24	10	13	15	8	14	20	17	10	17	15	7	17
Relative humidity (%)													
Normal*	93	94	92	85	81	79	77	84	87	92	94	93	[illegible]
1937 ..	57	73	—	—	—	—	78	81	85	93	93	94	—
1938 ..	89	84	83	72	71	71	78	84	87	85	90	92	[illegible]
1939 ..	88	86	83	77	81	73	77	86	87	88	91	94	[illegible]
Rainfall (inches)													
Normal	2·0	1·7	1·9	1·7	2·2	2·3	2·3	2·7	1·8	2·8	2·4	2·7	26
1937 ..	3·7	3·8	3·0	3·0	3·7	1·9	3·1	0·5	1·7	2·9	1·4	1·9	30
1938 ..	2·6	0·7	0·2	0·1	1·6	1·3	2·6	3·5	1·9	2·0	2·1	3·1	21
1939 ..	5·2	0·8	1·2	1·8	1·0	1·3	2·4	4·5	1·4	3·3	3·3	1·4	27
Average temperature (°F.)													
Normal	40	39	42	46	51	57	62	60	56	49	43	39	4
1937 ..	40	40	38	48	54	57	60	61	55	50	40	37	4
1938 ..	42	41	48	45	51	58	59	61	56	50	48	38	5
1939 ..	39	41	42	48	52	56	59	61	58	46	47	37	4
Daily maximum temperature (°F.)													
Normal	43	43	49	52	59	65	69	68	63	55	47	43	5
1937 ..	45	45	44	55	62	66	67	71	65	56	46	42	5
1938 ..	47	46	58	55	61	67	68	70	64	57	55	43	5
1939 ..	44	47	48	56	61	66	68	70	65	53	52	41	5
Nightly minimum temperature (°F.)													
Normal	36	35	36	39	44	49	54	53	50	44	39	36	4
1937 ..	35	35	32	40	46	48	52	52	46	43	35	32	4
1938 ..	37	36	39	35	42	49	50	52	48	44	42	33	4
1939 ..	34	35	36	39	43	47	51	53	50	39	42	33	4
Grass minimum temperature (°F.)													
1937 ..	30	33	—	—	—	—	48	46	42	36	31	28	—
1938 ..	32	32	35	28	35	43	47	48	36	—	38	32	[illegible]
1939 ..	31	32	32	34	37	40	47	49	46	36	39	31	[illegible]
Earth temperature at a depth of 1 *ft.* (°F.)													
1937 ..	—	—	—	—	—	—	61	62	57	52	46	40	—
1938 ..	41	41	44	46	50	55	59	62	58	53	50	44	[illegible]
1939 ..	41	41	42	46	50	56	59	60	60	51	48	43	[illegible]
Earth temperature at a depth of 4 *ft.* (°F.)													
1937 ..	—	—	—	—	—	—	57	59	58	54	50	45	—
1938 ..	44	43	44	47	49	52	55	58	57	55	52	47	[illegible]
1939 ..	44	43	43	45	48	52	56	57	59	54	50	47	[illegible]
Temperature increase between ground and 1000 *ft.* (*at about* 7 *h. at Mildenhall*) (°F.													
1937 ..	−0·6	+0·1	+0·6	−0·7	+0·6	−1·2	+1·5	+1·6	+3·0	+2·9	+1·7	+2·3	+
1938 ..	+1·3	−0·3	+5·9	+2·7	+0·2	−1·4	+0·1	+3·9	+2·9	+3·7	+1·4	+1·3	+
1939 ..	−0·2	+0·9	+0·7	+3·1	+2·2	+0·8	−0·8	+2·4	+2·1	+3·6	+0·6	+1·5	+

* For Cranwell, Lincs., from the Book of Normals, Section VI.

n normal values for Birmingham (Edgbaston) given by E. G. Bilham in "The Climate of the British Isles" (Macmillan & Co., London, 1938)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Cloudiness (tenths of sky covered)													
ormal*	7·2	7·0	6·6	6·4	6·5	6·5	6·9	6·4	6·0	6·6	7·0	7·3	6·7
37† ..	7·4	7·4	—	—	—	—	8·0	4·4	5·5	8·4	8·1	7·9	7·2
38† ..	7·9	8·5	8·1	6·9	7·1	7·6	7·4	7·1	7·0	6·3	7·0	7·4	7·4
39† ..	8·8	6·8	7·7	6·5	7·1	6·7	8·0	8·9	7·4	7·7	8·4	7·5	7·6
* For Birmingham at 9 h. and 21 h. to 1923; subsequently at 7 h. and 18 h. † For Leicester at 9 h.													
Days with fog													
ormal	7	7	7	3	2	1	3	1	5	5	8	10	59
37 ..	9	11	—	—	—	—	0	1	0	6	7	9	—
38 ..	2	0	5	0	0	0	0	0	0	2	2	1	12
39 ..	2	2	1	0	0	0	0	0	1	6	1	4	17
Hours of sunshine per day													
ormal	1·4	2·0	3·1	4·2	5·5	6·0	5·5	5·2	4·1	2·9	1·5	1·1	3·6
37 ..	—	—	—	—	—	—	3·1	5·5	4·3	2·0	1·6	0·7	—
38 ..	1·1	1·8	4·1	4·7	5·2	5·6	4·3	4·6	3·3	3·6	2·5	1·1	3·5
39 ..	0·9	2·7	2·5	5·3	5·7	6·6	4·9	4·5	3·6	2·6	1·1	0·7	3·4
Percentage of possible sunshine													
ormal	17	21	26	30	35	36	34	36	32	28	18	15	29
937 ..	—	—	—	—	—	—	19	38	34	19	20	9	—
938 ..	13	19	35	34	33	34	27	32	26	35	30	15	28
939 ..	11	28	21	38	36	39	30	31	28	26	13	10	26
Wind velocity (m.p.h.)													
937 ..	7	7	5	5	4	4·8	4·8	3·0	7·1	5·3	4·7	6·0	5·3
938 ..	11·1	12·2	8·4	5·1	6·4	8·4	6·6	5·5	4·7	8·6	9·6	9·1	8·0
939 ..	9·5	10·8	10·8	9·4	6·9	6·7	7·9	4·3	5·9	7·0	8·7	6·2	7·8
Smoke concentration at the centre of Leicester (milligrams per 100 cubic metres)													
937 ..	49	31	36	27	19	12	11	15	25	31	58	53	30
938 ..	39	37	41	34	18	15	16	17	23	26	31	28	27
939 ..	49	47	36	28	25	14	14	15	18	39	39	55	32
Sulphur dioxide concentration at the centre of Leicester (milligrams of SO_2 per 100 cubic metres; multiplied by 0·35, the numbers represent volumes of SO_2 per 100 million volumes of air)													
937 ..	32	28	31	26	17	14	16	13	18	33	49	45	27
938 ..	37	36	43	29	21	14	9	15	20	25	32	35	26
939 ..	39	42	29	25	20	14	14	11	21	31	34	44	27
Rate of sulphation of lead peroxide at the centre of Leicester (milligrams of SO_3 per day, per 100 cm.² of PbO_2 surface)													
937 ..	4·3	4·3	4·3	3·4	2·2	1·5	1·8	1·7	2·7	3·7	5·0	6·0	3·4
938 ..	4·8	3·7	3·7	4·3	1·9	1·4	1·5	1·7	2·0	3·6	4·2	4·4	3·1
939 ..	5·8	4·7	3·1	3·1	2·6	1·9	2·0	1·5	2·3	4·2	5·2	5·9	3·5
Rate of deposition of sulphates at the centre of Leicester (milligrams of SO_4'' per month, per 100 cm.² of ground)													
937 ..	15	17	14	14	12	7	15	8	11	17	12	15	13
938 ..	18	9	7	6	7	7	8	13	9	14	16	14	11
939 ..	20	11	10	9	6	7	11	9	7	14	14	17	11
Rate of deposition of soluble matter at the centre of Leicester (milligrams per month, per 100 cm.² of ground)													
937 ..	36	46	36	16	28	22	24	20	25	30	21	31	28
938 ..	38	24	21	14	17	18	25	29	24	35	37	34	26
939 ..	44	25	24	26	19	26	38	27	17	38	39	39	30
Rate of deposition of insoluble matter at the centre of Leicester (milligrams per month, per 100 cm.² of ground)													
937 ..	98	88	66	54	68	51	67	62	64	86	56	52	68
938 ..	81	52	63	46	28	49	50	58	61	93	87	60	61
939 ..	80	84	54	69	51	52	66	68	49	55	105	87	68

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